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AIRCRAFT GUIDANCE AND CONTROL SYSTEM SYNTHESIS FOR APPROACH AND LANDING STUDIES

JOHN S. KOZINA
LEAR SIEGLER INC.
MANAGEMENT SERVICES DIVISION

TECHNICAL REPORT AFFDL-TR-71-60

JUNE 1971

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by the Management Services Division of Lear Siegler Inc., 4001 Lincoln Blvd., Oklahoma City, Oklahoma in support of Contract No. F33615-70-C-1064 and under guidelines established by the Systems Integration and Flight Experimentation Branch (FGS), Flight Control Division, Air Force Flight Dynamics Laboratory. This is the final report of a program of synthesis and in-flight optimization and evaluation of navigation, guidance, flight control and display concepts covering the period of 1 August 1969 thru 31 December 1970.

Special acknowledgment is afforded to Mr. Sigfried Kneymeyer, Consultant to the Flight Control Division for his conceptual approach inputs which so greatly added to the overall program objectives. We also extend our sincere appreciation to Mr. Alfiero Longiaru, Group Leader, and Mr. Aivars Smitchens, Task Engineer of Systems Integration and Flight Experimentation Branch (FGS), for their assistance and guidance.

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R & D SYSTEMS WERE SYNTHESIZED AND EVALUATED IN FOUR T-39A AIRCRAFT. FLIGHT CONTROL AND DISPLAY CONCEPTS WERE DEVELOPED TO OPTIMIZE NAVIGATION AND GUIDANCE REQUIREMENTS. SUCCESSFUL AUTOMATIC APPROACHES THROUGH FLARE AND TOUCHDOWN WERE ROUTINELY ACCOMPLISHED EVEN UNDER MINIMUM WEATHER CONDITIONS. THUS, THE SYSTEMS AS SYNTHESIZED PROVIDED A SOLUTION TO THE BASIC PROBLEM.

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ABSTRACT

This report concerns the problem associated with Military Aircraft approach and landings. R & D Systems were synthesized and evaluated in four T-39A Aircraft, two at Wright-Patterson AFB, Ohio and two at Randolph AFB, Texas. Flight control and display concepts were developed to optimize Navigation and guidance requirements. Successful automatic approaches through flare and touchdown were routinely accomplished even under minimum weather conditions. Thus, the systems as synthesized provided a solution to the basic problem. Continuance of the study in control and display is recommended in the areas of decrab vs. the forward slip, the implementation of moveable rate displays to augment basic displays and aircraft rollout guidance and control requirements.

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GLOSSARY and ABBREVIATIONS

ABBREVIATION	DEFINITION
AAC	Angle of Attack Computer
ADI	Attitude Director Indicator
Automatic	All Systems Coupled to Auto-Pilot
AVRI	Altitude and Vertical Rate Indicator
Coupled	Automatic Flight Control System Controlled by the Flight Director Steering Commands
ET	Elapsed Time
FDC	Flight Director Computer
Force Fade	Force Removed from Force Wheel through Synchronization. AFCS Facility
FPAC	Flight Path Angle Computer
GPIP	Glide Path Intercept Point
HSI	Horizontal Situation Indicator
IRATE	Interim Remote Area Terminal Equipment
LALSCD	Low Altitude Low Speed Control Development
LSI	Lateral Situation Indicator
Manual	Standard Flight Control w/o AFCS
MEPADD	Mechanical Path Angle Director Display
PCI	Peripheral Command Indicator
PIFAX	Pilot Control Display Factors Program
Roll Sync AFCS	Provide Force vs. Attitude and a Wings Level Reference within ± 10° and Rate Stabilized Force Steering Above ± 10°

GLOSSARY
and
ABBREVIATIONS (Con't.)

ABBREVIATION	DEFINITION
Semi-Automatic	AFCS Engaged, Force Wheel, Steering Employed, AFCS Not Coupled
STATE	Simplified Tactical Approach and Terminal Equipment
TALAR	Tactical Approach and Landing Radar
VVI	Vertical Velocity Indicator
Weather Minimums	Zero Visibility Landing Study

LIST OF SYMBOLS

SYMBOL	DEFINITION
Flight Control System Parameters	
δ	Control Surface Angle (Degrees)
δa	Control Surface Angle (Aileron)
δe	Control Surface Angle (Elevator)
δr	Control Surface Angle (Rudder)
$K\psi$	Yaw Displacement Gain (Volts)
$K\phi$	Roll Displacement Gain (Volts)
$K\theta$	Pitch Displacement Gain (Volts)
λ	Bar Deflection (Inches)
Beam Parameters	
μa	Micro Amperes
G.S.	Glide Slope
Loc.	Localizer

LIST OF SYMBOLS (Con't.)

SYMBOL	DEFINITION
Aircraft Parameters	
α	Angle of Attack
γ	Flight Path Angle
θ	Aircraft Pitch Attitude
ϕ	Aircraft Roll Attitude
ψ	Aircraft Heading
V	Velocity
g	Gravity induced by Acceleration
IAS	Indicated Air Speed
h	Altitude
$\dot{h}$	Altitude Rate
β	Sideslip Angle

SECTION I

INTRODUCTION

This report was prepared to compile information on the recent phases of a continuing USAF investigation of advanced concepts having the potential to enhance the precision and reduce pilot workload, especially during the approach and landing of aircraft.

The investigation of many of these concepts has taken place over the span of the last seven years. It has involved the design and test of instruments and systems installed in simulators and test-bed aircraft. Recognition of earlier experiments and of later applications in other test vehicles is acknowledge, but this report will deal specifically with work and tests accomplished on four T-39A aircraft. Two of the T-39A test-bed aircraft were based at Wright-Patterson Air Force Base, Ohio and two at the Instrument Pilot Instructor School at Randolph Air Force Base, Texas. Figure 1 is representative of the test aircraft.

The report describes the concepts investigated, the experimental approach to the evaluation of each concept, the mechanization of the equipment used for testing and summarizes test results. The presentation of the material herein is not intended as a blueprint for specific design engineering, but rather as a description of hardware utilized as tools to explore and validate the advanced concepts being investigated.

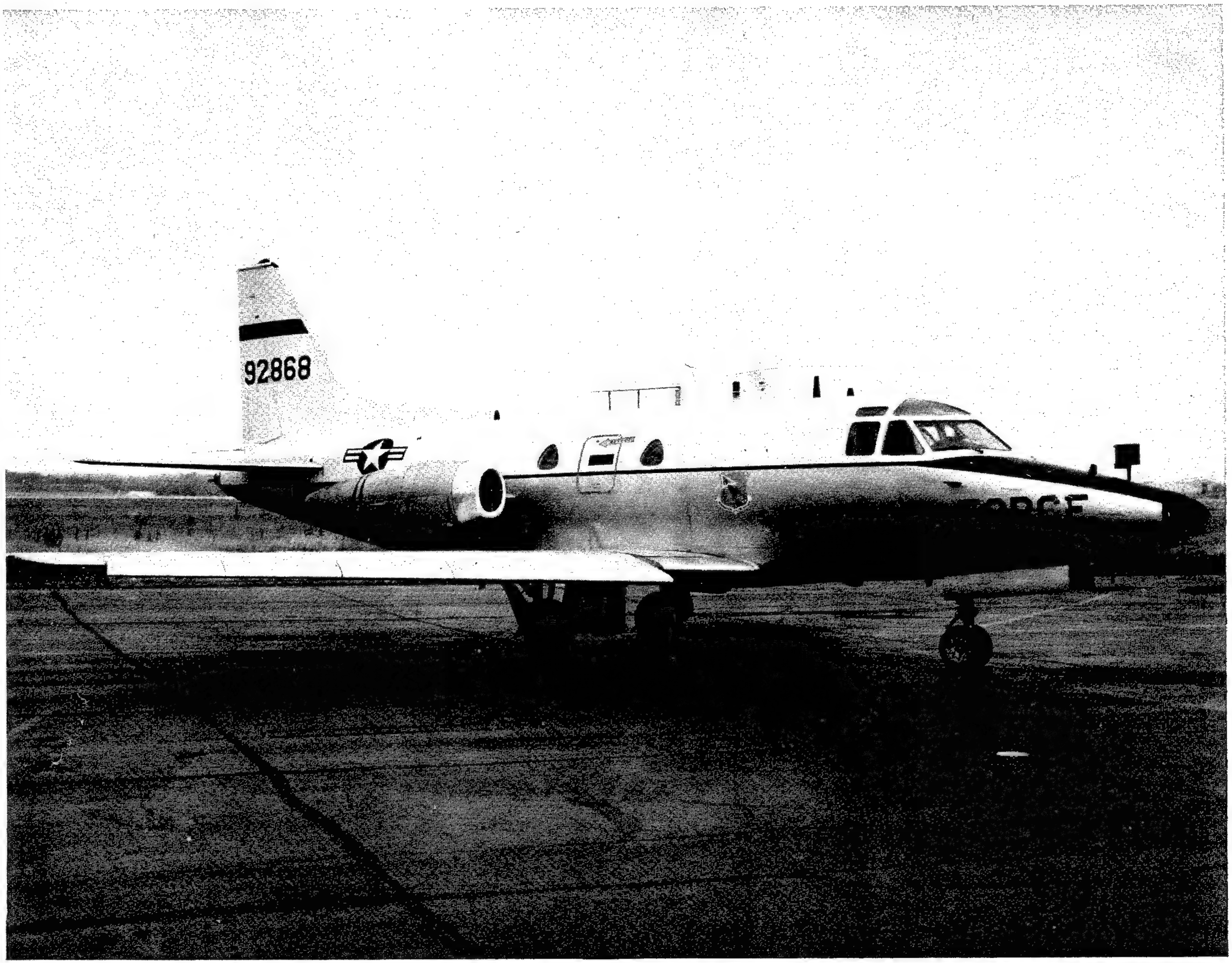


Fig. 1: T-39A Test Aircraft

Reference to the Table of Contents will indicate the arrangement of the material presented. The section devoted to Design Approach describes the problem areas and the methods chosen for solution. Succeeding sections present detailed information on mechanization and samples of the data obtained.

The bibliography lists publications which contain some of the history of the concepts mentioned and descriptions of the broad program considered in this report.

SECTION II

AREAS OF INVESTIGATION

Early in the 1960-1970 decade, advanced planning was undertaken for supersonic transport operations. The investigation of the slow-speed regime as it pertained to the approach and landing phase became the focus of an in depth study called the USAF Pilot Control-Display Factors Program (PIFAX). The program was sponsored by the Supersonic Transport Office of the Federal Aviation Administration and was under the technical direction of the Flight Control Division, Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. It had as its objective a conceptual definition of those aspects related to the approach and landing of an aircraft through instrument guidance.

The PIFAX philosophy, while accepting various degrees of automaticity, insisted that the pilot be flight commander at all times. To keep the pilot in the loop and apprised of the total flight situation, additional displays providing unique flight information and approach progress annunciation were incorporated. Automatic control would be acceptable only as an aid for the pilot to accomplish his task of flying the aircraft.

The PIFAX investigation included an examination of degrees of

automatic control between full manual and full automatic. The flight profile extending from the Middle Marker to touch-down was the primary area for collection of experimental data.

ILS or GCA guidance approximately to the Middle Marker was generally accepted as SOP. Beyond this point the pilot was expected to go visual and complete his landing; standard procedure called for automatic flight control systems to be disconnected at the Middle Marker. One objective of this program was to enhance the capability and precision of automatic controls as tools available to the pilot during this critical terminal phase. The Ground Controlled Approach (GCA), using Precision Approach Radar, could be useful in bringing the aircraft to the runway threshold, the problem being to fly the aircraft within the converging window of the approach path. An investigation was initiated under PIFAX to provide improved vertical path guidance to the runway threshold. Improvements in ILS equipment performance minimized lateral guidance problems to the touch-down point; however, rollout guidance requirements were examined and the transition from rollout to go-around was investigated.

As the scope of the progtam developed, landing aids with potential application to a tactical situation were studied. The T-39A aircraft used in the PIFAX program were assigned

tasks in a new program intended to develop urgently needed technology for low visibility approach and landing capability at austere landing sites in a tactical environment. Studies in this area were grouped under the title of the IRATE Program.

Exploratory work with Heads-Up Displays was initiated to provide the pilot with guidance information in his field of vision during approach and landing. This area of investigation was directed toward elimination of problems associated with the transition from Instrument to Visual flight reference. One remaining area of investigation was undertaken to provide terminal guidance to touchdown in the longitudinal plane (Flare), thus total capability for approach and landing through touchdown could be realized utilizing Pilot Displays.

SECTION III

DESIGN APPROACH

The concepts discussed herein result from the philosophy that the pilot must be flight commander at all times, he further must be "in the loop" at all times, and he must have available the displays to provide him with the intelligence necessary to properly exercise his absolute authority over the total system. Simultaneously, serious consideration was given to those facilities that would reduce pilot work load by providing him with known precision incremental control inputs to augment expanded panel display.

Conceptually few areas were overlooked and new or improved designs were incorporated into pilot displays, annunciation, mode selection and control. Additional signal and control parameters were introduced to assist the pilot in assessing aircraft performance, flight situation, and landing progress. Although installations and missions varied, similar equipment was installed in all four aircraft. Figure #2 represents a typical equipment installation.

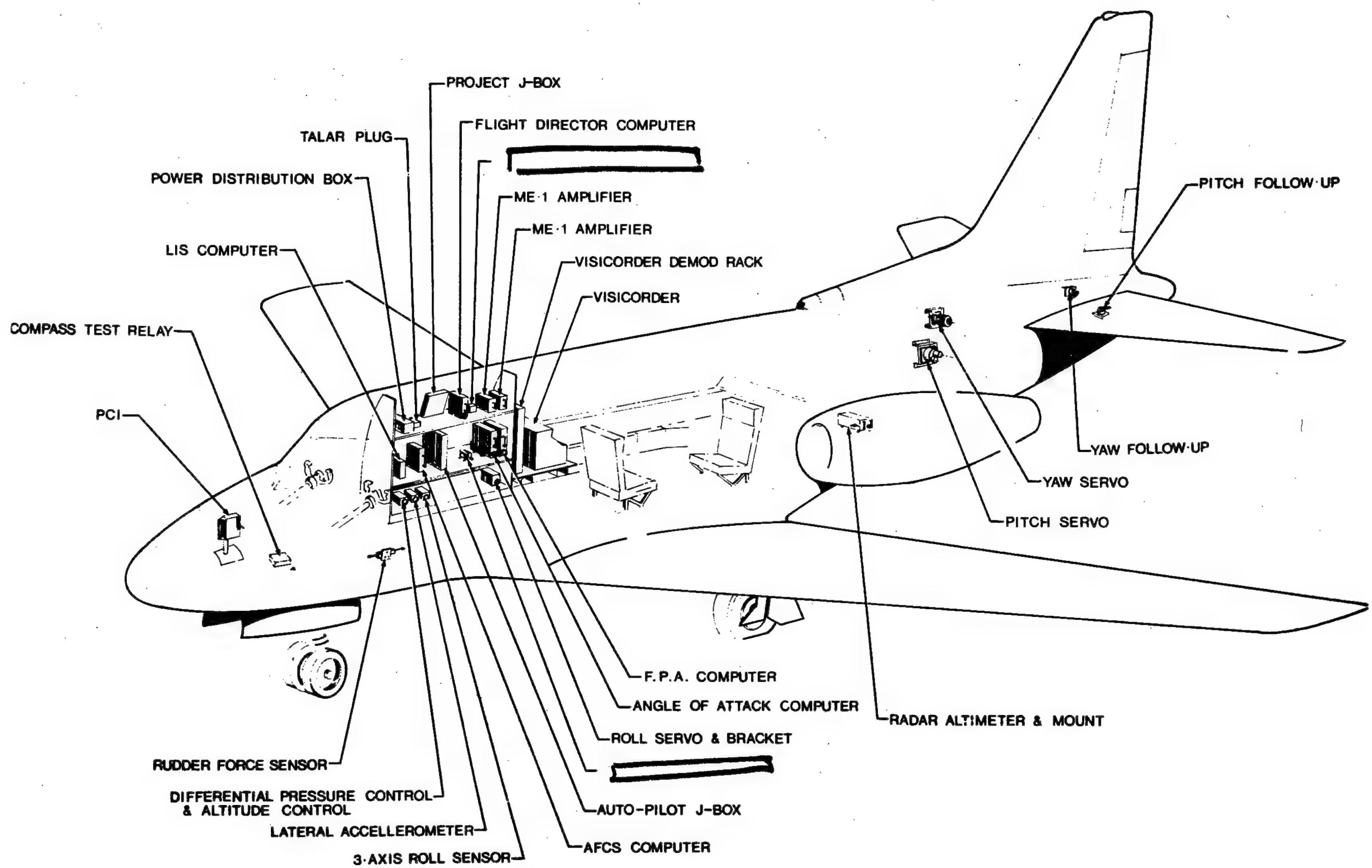


Fig. 2: Typical Equipment Installation

An Automatic Flight Control System was fully integrated with the Flight Director Commands and mode logic. Three Axis Force Steering was incorporated, thus providing an additional mode of operation (i.e., Semi-Automatic), but maintaining the pilot's absolute control over the AFCS. The AFCS circuits were altered to provide improved pilot management over the system through the force wheel. Circuits such as "Force Fade" in the longitudinal axis and "Roll Synchronization" in the lateral axis were mechanized. New Flight Director modes and/or situations were established and annunciated to obtain precision over a broader approach and landing requirement, including the GCA approach.

Signal conditioning, such as glide slope extension circuits, variable limiters, signal reduction and signal fade-in/fade-out circuits provided the necessary capability and flexibility to investigate the total approach and landing phase.

Unique control and display circuits were implemented to provide both precision and trend information. These include a "Side Slip" mode which was evaluated to reduce or eliminate the lateral or localizer cross track error associated with a decrab manuever. A localizer rate display was used to provide the pilot with the localizer cross-track situation and the trend resulting from the changing rates displayed.

Systems tested in the four T-39A aircraft include Radar Altimeter, Flight Path Angle Computer, improved Flight Directors and Automatic Flight Control with Force Wheel Steering and Split Axis provisions. Aids and auxiliaries for the Instrument Landing System and Ground Controlled Approach have been tested in these aircraft.

The displays and their utilization are of prime importance. Figure 3 depicts a standard T-39A Pilot Instrument Panel. Figure 4 is the pilot's instrument panel, after modification, in one of the test aircraft.

The instruments to be described were designed to provide the pilot with essential raw data, the command data derived from the raw data, and the trend established as a function of obeying the command data. In addition, the approach and landing situation is well defined. The text will first describe the instruments individually, describe their uniqueness, then group them in a manner as to display to the pilot the above information in the most efficient manner.

The Attitude Director Indicator, Figure 5 is similar to and contains all the information that is displayed in a standard Air Force type ARU-2/A ADI. This includes aircraft roll and pitch attitude, raw Glide Slope deviation, Flight Director lateral and longitudinal steering commands, rate of turn and slip information. In addition, the unit incorporates many

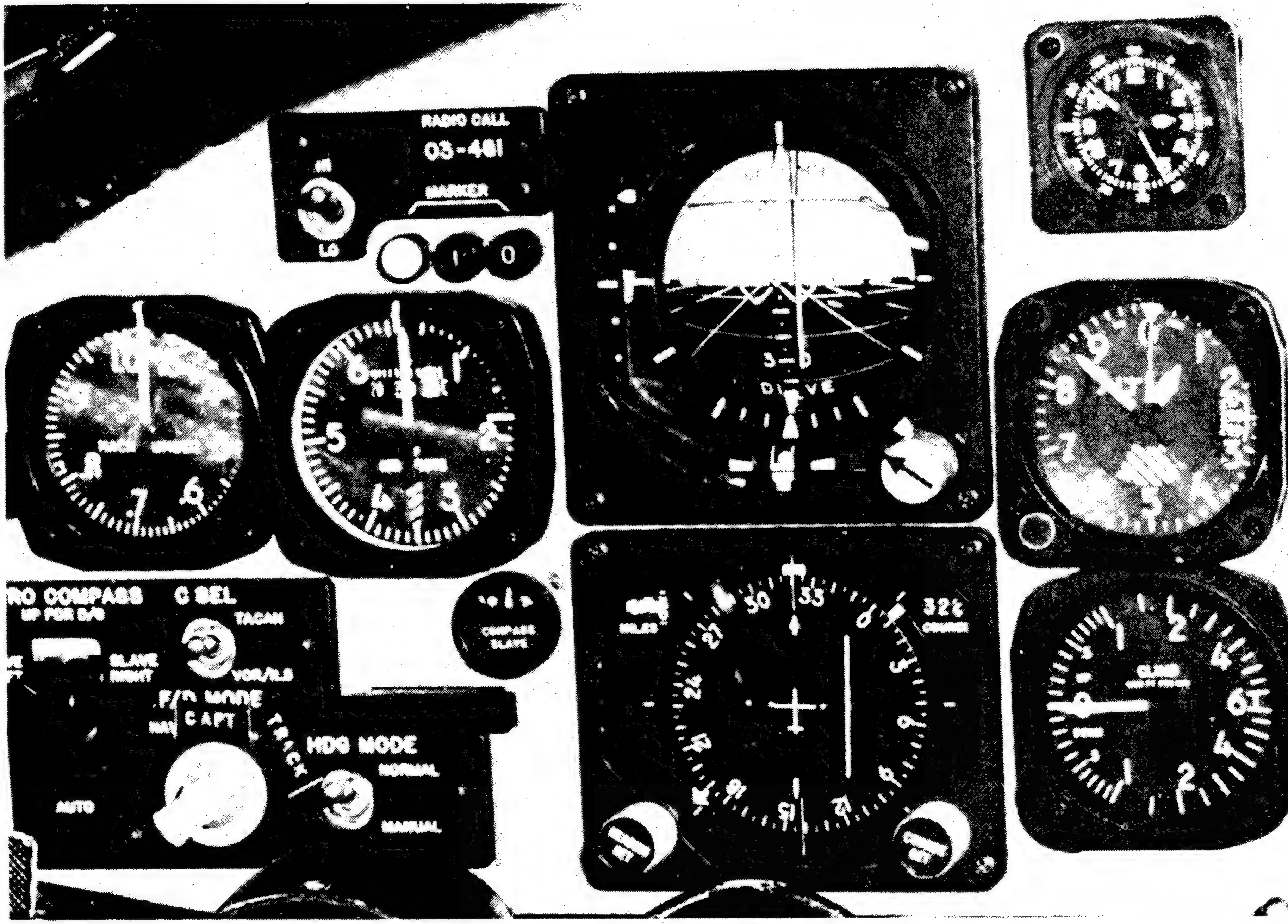


Fig. 3: Pilot's Instrument Panel Before Modification

Fig. 4: Pilot's Instrument Panel After Modification

changes such as the semi-circular symbol for the aircraft reference, improving the readability of small pitch angles. The top half of the sphere was painted blue (sky) and the bottom half brown (ground) to enhance the general appearance and to closer approximate the "real world." Five-degree increments were added to the bank markings.

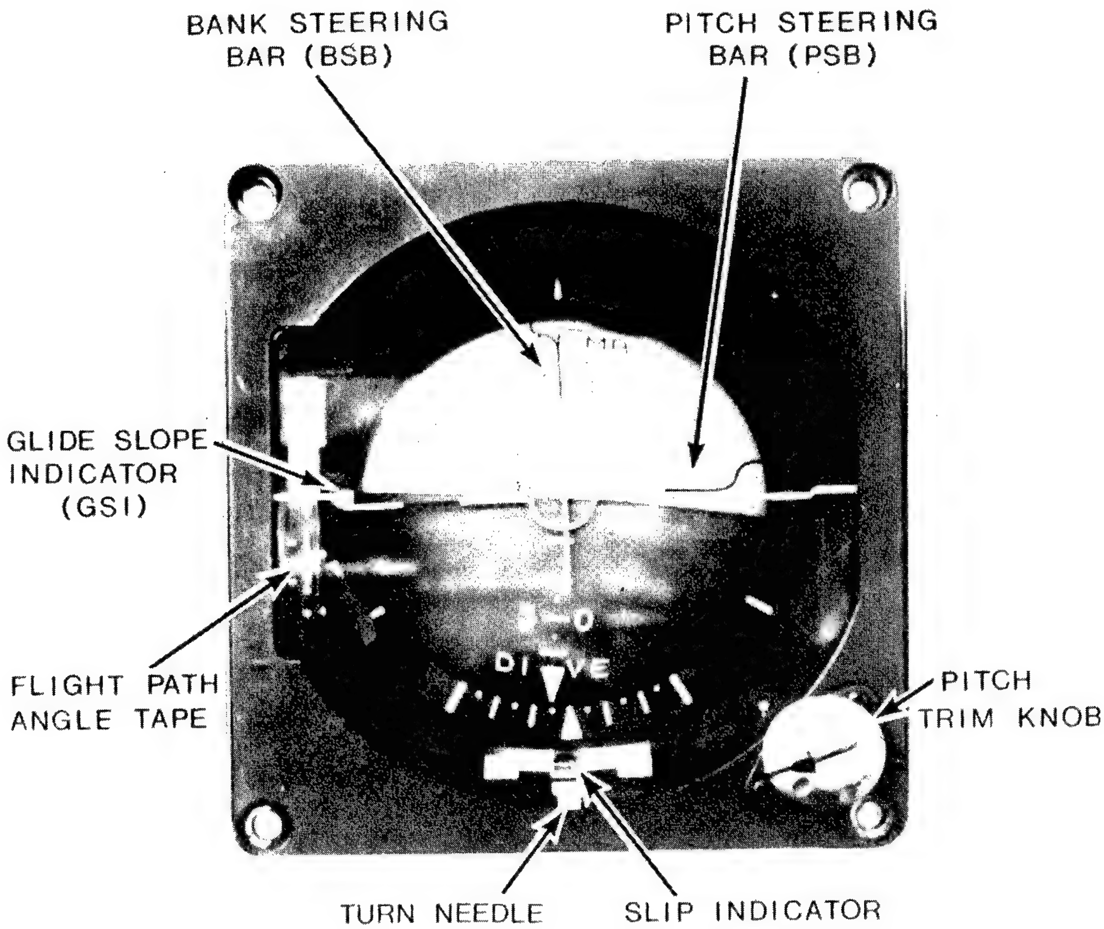


Fig. 5: Attitude Director Indicator

A servoed tape which displays a direct flight path angle readout in degrees, and easily discernible to $\frac{1}{4}°$ increments has been mechanized on the left side of the instrument where the scale of raw glide slope information would normally be. The GS scale has been moved slightly inboard of the FPA scale and both displays utilize the same "O Center" lubber line. Finally, the command bars are approximately half the thickness of the standard unit enabling the pilot to center them with greater precision.

A variation of this indicator, one commonly referred to as the "V" ADI, is being flight tested to evaluate a runway rate of closure or a rising runway concept. (See Figure 6.) It displays all the information contained in the unit described above and in addition has been modified to include a qualitative display of absolute altitude in the form of two rows of dots.

Controlled by a radio altimeter that provides absolute altitude information, the rows of dots separate by approximately 5° at 1000' to signify that the display is operational. At a preset altitude (which is adjustable between 150 and 75 feet) the rows of dots will swing open, angularly proportional to the decreasing altitude, so that at touchdown each row of dots will have spread outward and intersected its respective indice. The intent is to provide the pilot with a real world display which approximates the sides of the runway opening up

with decreasing altitude. In addition to the altitude readout provided, a localizer displacement feature is also available,but at this time has not been incorporated into the flight test program. This feature would indicate displacement from the runway centerline through rotation of the simulated runway.

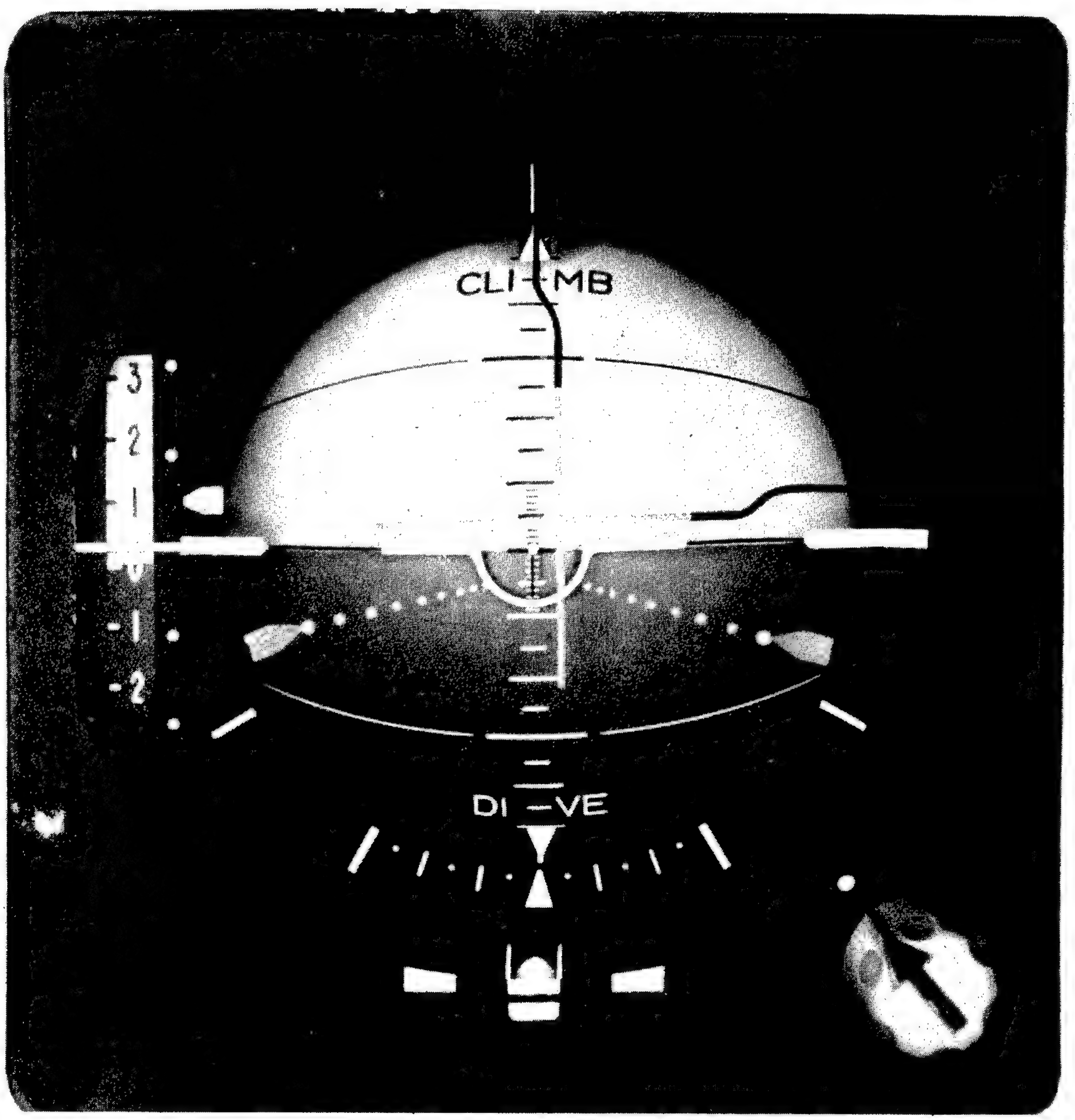


Fig. 6: "V" Attitude Director Indicator

The Horizontal Situation Indicator (HSI) is a standard Air Force type AQU-2A. (See Figure 7.) The display consists of the azimuth ring with aircraft magnetic compass heading read under the fixed lubber line at the top of the ring, and the reciprocal read at the bottom of the ring. A fixed

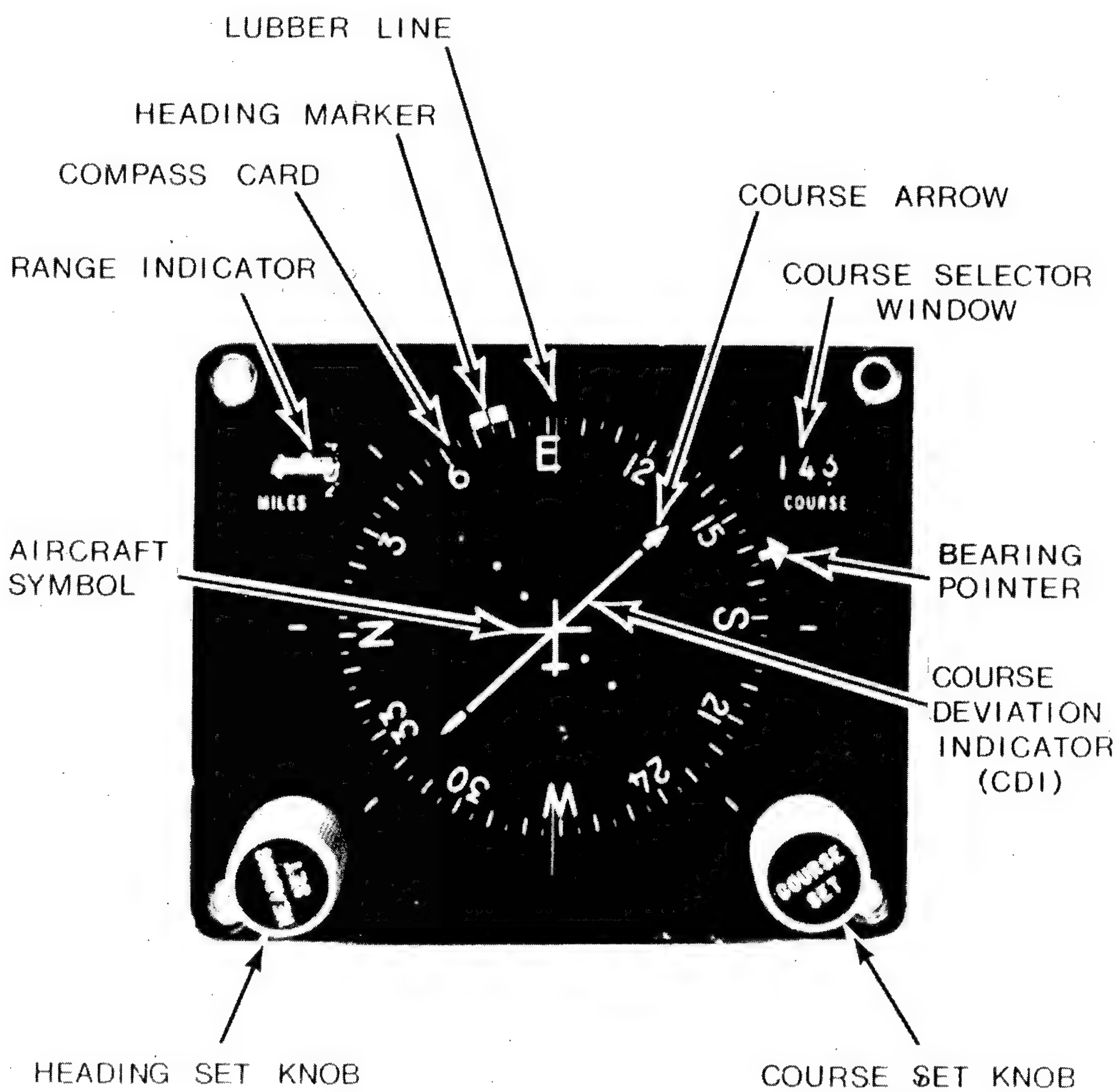


Fig. 7: Horizontal Situation Indicator

aircraft symbol is provided for reference. A bearing pointer indicating the heading "to the station" and the reciprocal is provided at the outer edge of the azimuth ring. A Command Heading indice is also provided at the outer edge of the azimuth ring. A course pointer to indicate the command course and its reciprocal dominates the center of the azimuth card.

The center section of the pointer is the Radio Deviation Indicator. A To/From indicator appears between the symbolic aircraft and the course marker and indicates approach to or departure from a selected radio facility. where?

Manual heading and course set knobs for establishing the desired heading and course are at the bottom of the instrument; however, these were seldom used during project flights since full advantage was taken of the Remote Heading and Course Command circuits described later. Facilities were incorporated on the pilot's control wheel to precisely position either the course or heading, thus alleviating the necessity of the pilot reaching over the wheel to readjust the heading and/or course set knobs on the instrument. The convenience of the remote heading set was especially accepted by the pilots since normal flight profiles require considerable resetting. Little advantage was seen in the remote course set feature, primarily due to the fact that this parameter is normally never changed during the approach and landing phase of the mission.

To the right of the Attitude Director Indicator is an instrument designated an Altitude/Vertical Rate Indicator (AVRI). This instrument (Figure 8) serves primarily as an aid in the aircraft approach and landing. The servo-driven tape units provide the pilot with a numerical readout of instantaneous vertical velocity. The vertical velocity is presented by a white triangular pointer moving over the fixed scale, calibrated in 1000 ft./min.

The absolute altitude information is provided by a vertical tape in sections of white and black separated by a red indicator (ground reference). Where is it? At a preset altitude, the white section appears. As the aircraft descends, the area of white tape exposed is reduced by the tape moving upward; this gives the pilot a visual sensation of descent. The design philosophy of the instrument, beyond the normal indications, becomes apparent at flare initiation. At this point, (50' in a T-39A aircraft), the radar tape is approximately at the point of the normal rate of descent of the aircraft (650' - 700'/minute for a 3° Glide Slope). At flare initiation, and utilizing a "one step", minus 1 degree flight path angle reference, the vertical velocity begins to decay to its referenced

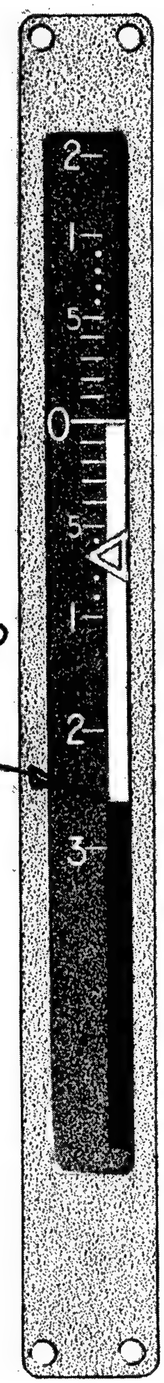


Fig. 8: AVRI

value of approximately 180 - 200 ft./minute. The resulting appearance at flare initiation is that the Vertical Velocity Indicator (indicating a reduction in the rate of descent) basically paces the decaying altitude readout. This provides a positive indication that a flare has indeed been initiated plus a quantitative indication of its progression. Normal indication would have the Vertical Velocity Indicator stop at a nominal 180 ft./minute rate of descent and the Altitude tape continue to zero at touchdown.

Located directly below the Attitude/Director Indicator is another experimental unit designated the Lateral Situation Indicator. (See Figure 9). Used primarily from the Middle

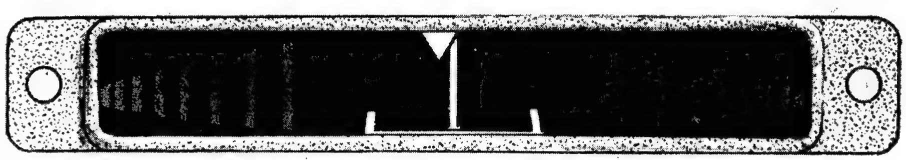


Fig. 9: Lateral Situation Indicator

Marker through touchdown and rollout, this unit, as its name implies, provides the pilot with the complete lateral situation at a glance. As mechanized, three types of information are displayed: (1) aircraft heading vs. runway heading (normally called course error but in reality the aircraft crab angle

to the runway). The indicator is scaled to provide a full scale deflection for 10° of course error. (2) a runway symbol denoting aircraft position relative to the runway centerline. This is in reality an expanded localizer deviation calibrated to symbolize one-half the threshold width (150 ft.) of a 10,000 ft. runway, using a Category II ILS beam as the criterion for establishing the micro amp/foot calculation. (3) localizer deviation rate. Seen at each side, this display was intended to provide trend information to augment the information displayed by the runway symbol. The display consists of a series of electroluminescent segments which, when excited with the proper electronics, could be made to illuminate progressively and provide the impression that the elements lighted were all moving to the right or left as the case may be. Thus, whenever the runway symbol is displaced, the moveable rate field would immediately notify the pilot if the situation was getting better or worse without his having to actually see (or look for) the physical movement in the runway symbol.

Located to the left of the ADI is the Speed Error Indicator (Figure 10). The Speed Error is denoted by the moving pointer which when mechanized provides a nominal ± 10 knot full scale indication. Speed errors greater than this would cause a yellow emitting electroluminescent rectangle (at the appropriate end) to illuminate. The philosophy is to move the throttle with the indication ie: pointer high/move throttles forward.

A rate field, identical to the one described in the earlier discussion of the Lateral Situation Indicator, is also employed to provide trend information. Philosophy is also the same, in that the trend information augments the basic display by eliminating the need for lengthy interpretation by the pilot who, with a little practice, could add precision to any manual speed control requirements.

The instruments described make up the basic pilot display group. Combined with the standard pitot/static flight instruments they are grouped efficiently and provide monitoring of all essential raw and computed command data. In addition the facilities are provided to present the trend data which appears to hold much promise as a control and/or display parameter. The typical display appears in Figure 11.

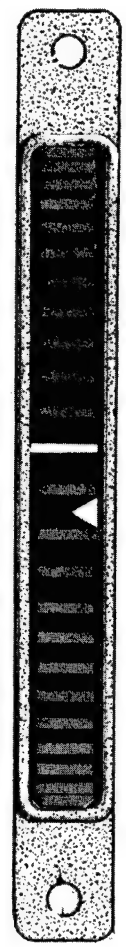


Fig. 10: Speed Error Indicator

The instruments are grouped in a "T-Scan" configuration designed to provide as much of the flight profile and landing situation in as small an area as possible. All lateral displays are referenced to the vertical portion of the T and all longitudinal displays are referenced to the horizontal portion of the T.

The complete lateral situation is contained in the vertical plane. (See Figure 12). Starting from the top, the lateral steering command is superimposed on the aircraft roll

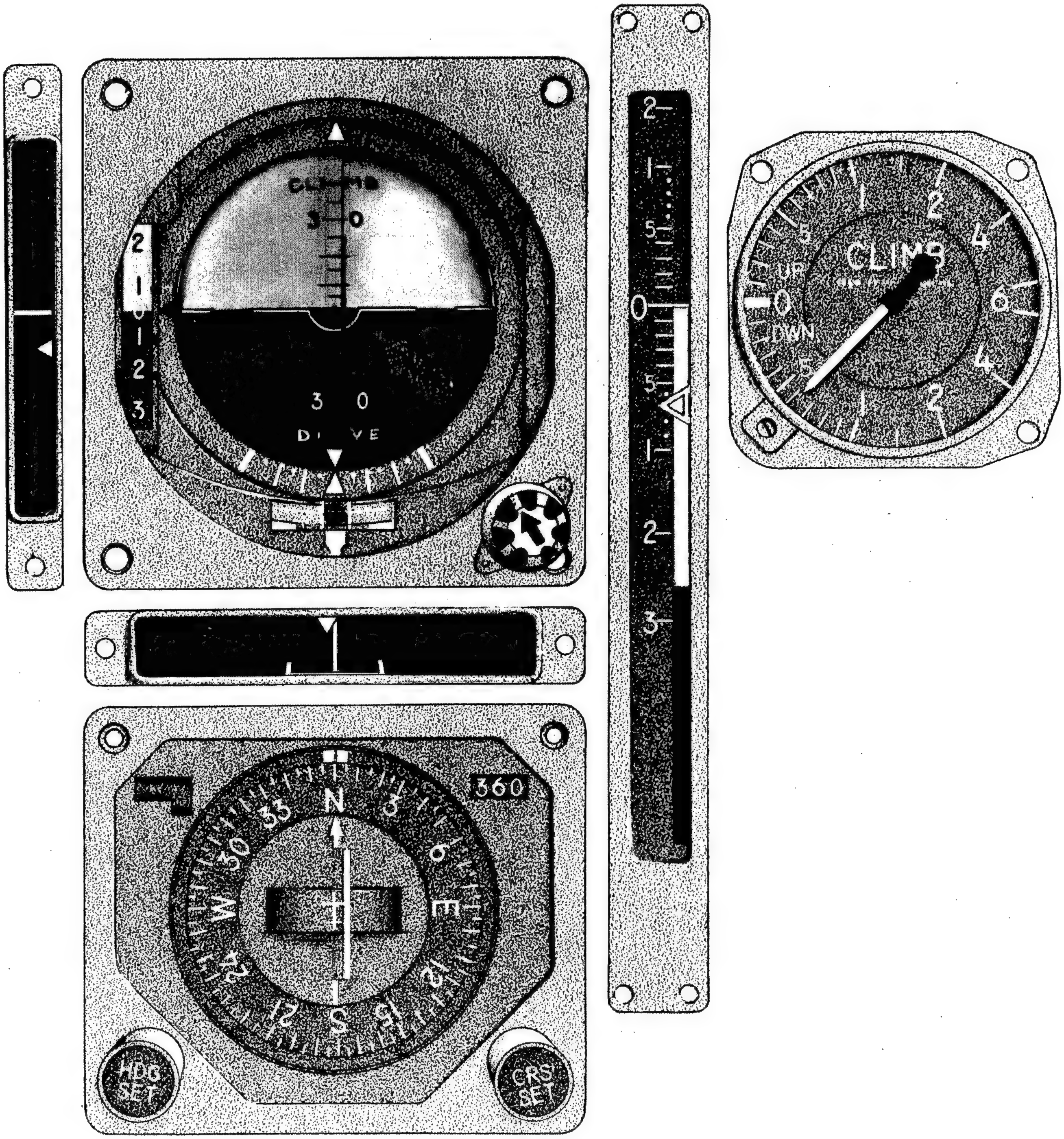


Fig. 11: Pilot Display Group

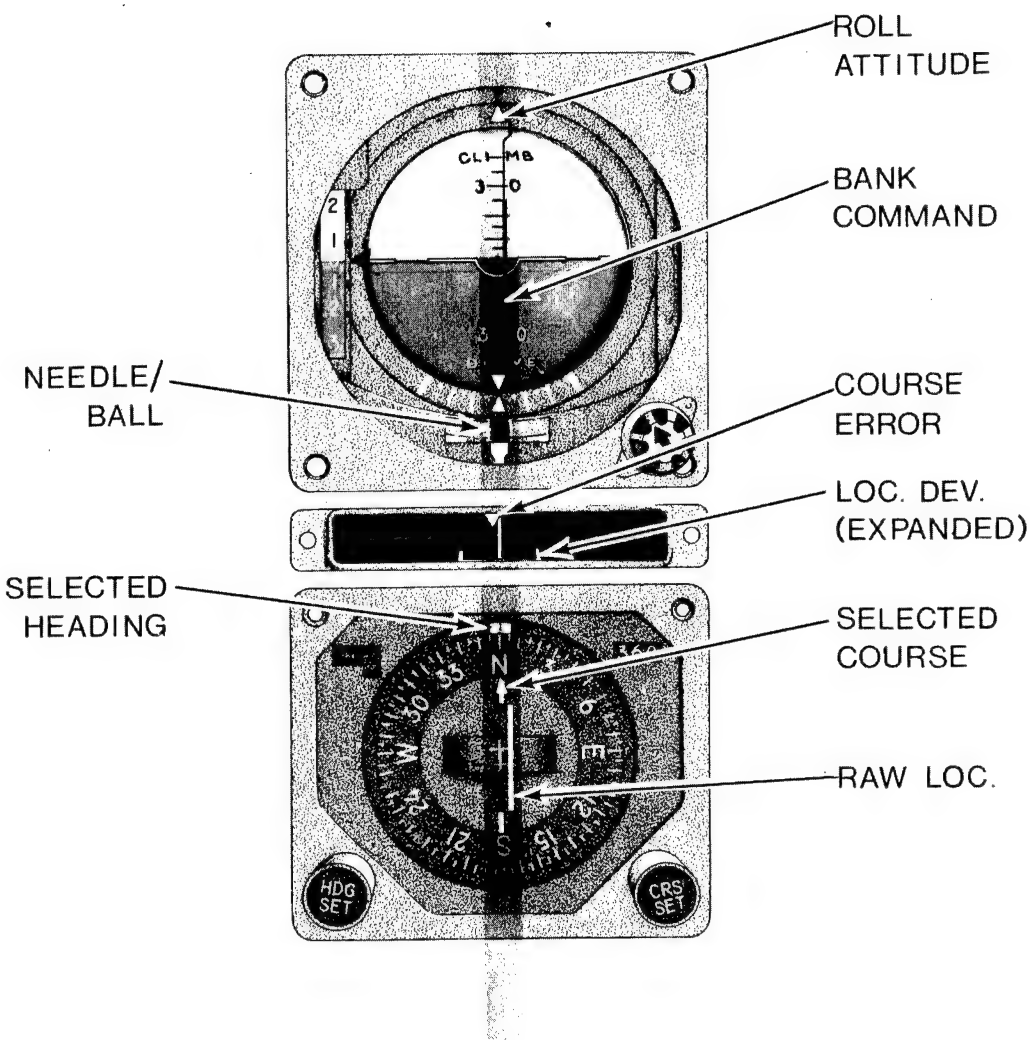


Fig. 12: Lateral Displays of the T Scan

attitude. On the ADI, directly below, the rate of turn and turn coordination is displayed. Next, the crab angle to the runway and the aircraft position laterally to the runway on the LSI. Last, the runway heading relative to the aircraft heading and localizer signal deviation is shown on the HSI. With exception of the course error with its resulting crab angle due to cross winds, the total lateral display is null seeking which in practice would result in a straight vertical line and no movement from the lateral rate field.

The longitudinal situation is contained in the horizontal plane. (See Figure 13). From the left, the speed error and speed error rate are displayed on the SEI computed from the specific speed control system installed in the aircraft. (Several were evaluated.) Though not specifically a longitudinal computation, an "ON SPEED" situation is necessary to establish and maintain an optimum longitudinal display, thus it must be placed into the prime area of pilot scan.

Moving right, a direct readout of the aircraft's flight path angle is incorporated in the Attitude/Director Indicator; also displayed, in a horizontal line, is the raw glide slope deviation and the pitch steering computation superimposed over the aircraft pitch attitude. Further to the right, the instantaneous vertical velocity and absolute altitude are displayed. The latter does not become important until final stages of the approach and landing phase as described under

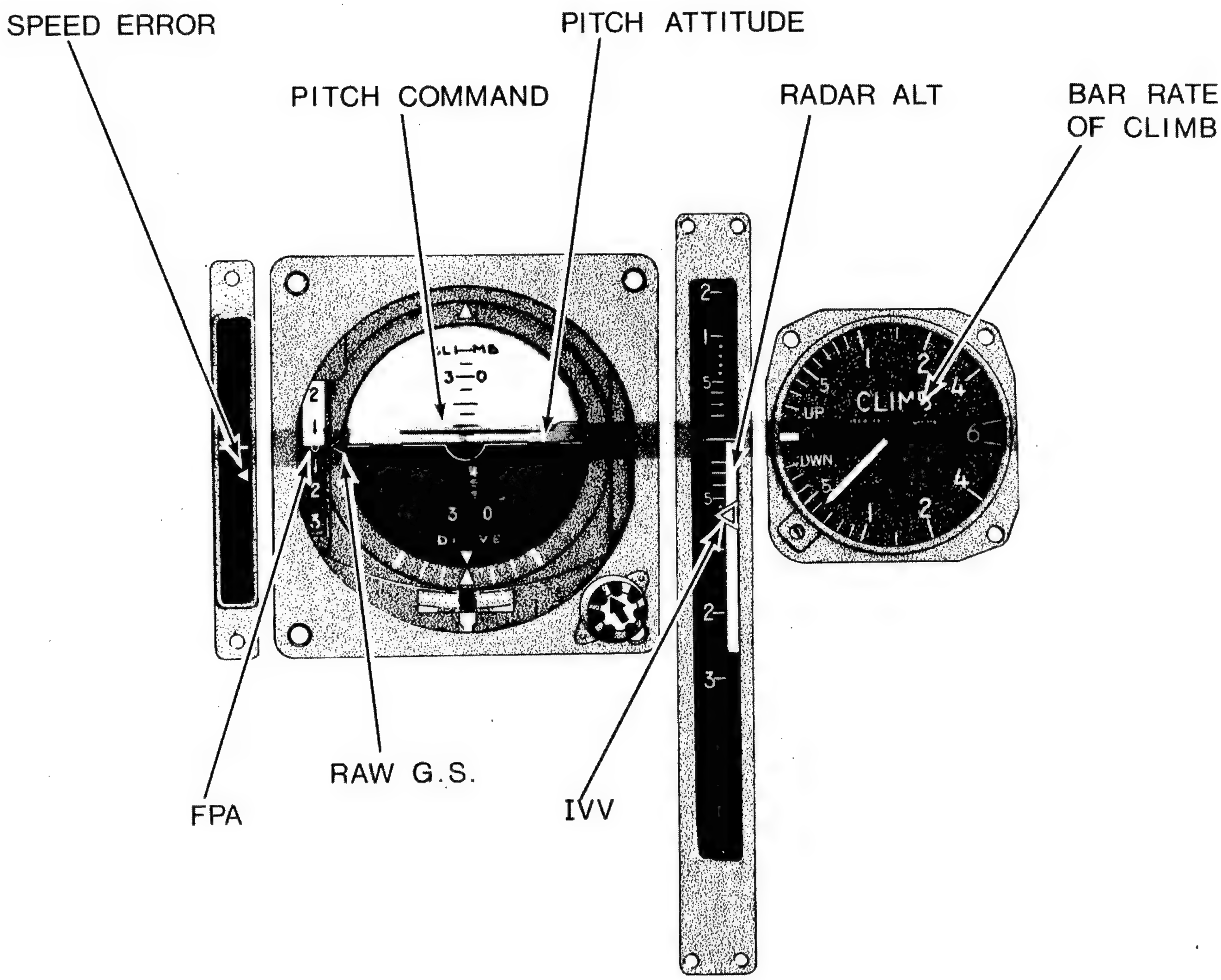


Fig. 13: Longitudinal Displays of the T-Scan

the AVRI. (See Figure 8, Page III-11).

Immediately to the right of the instantaneous vertical velocity indication is the Rate of Climb indicator (standard T-39A equipment) which is utilized as a long-term cross reference to the AVRI. Thus, the pilot has in a very small area displayed and easily interpreted: speed error, speed rate, the aircraft flight path angle, glide slope deviation, pitch attitude, vertical velocity and rate of closure to the runway.

The raw, computed and resultant data provide the pilot with the total approach profile and a simple and direct cross-check of the parameters, whether they are the result of an automatic system, the result of his own inputs, -- or both. This total display concept has evolved from the "Pilot in the Loop" philosophy.

Utilizing this concept, one T-39A aircraft has been involved in an active weather-minimum's study which, in part, is investigating the qualitative requirements of pilot displays under actual weather minimums. The investigation was initiated with a single pilot display; however, the test aircraft has been modified to include the installation of dual command and performance displays. (See Figure 14.)

In addition to the primary experimental displays provided for each pilot, dual flight director computers were installed

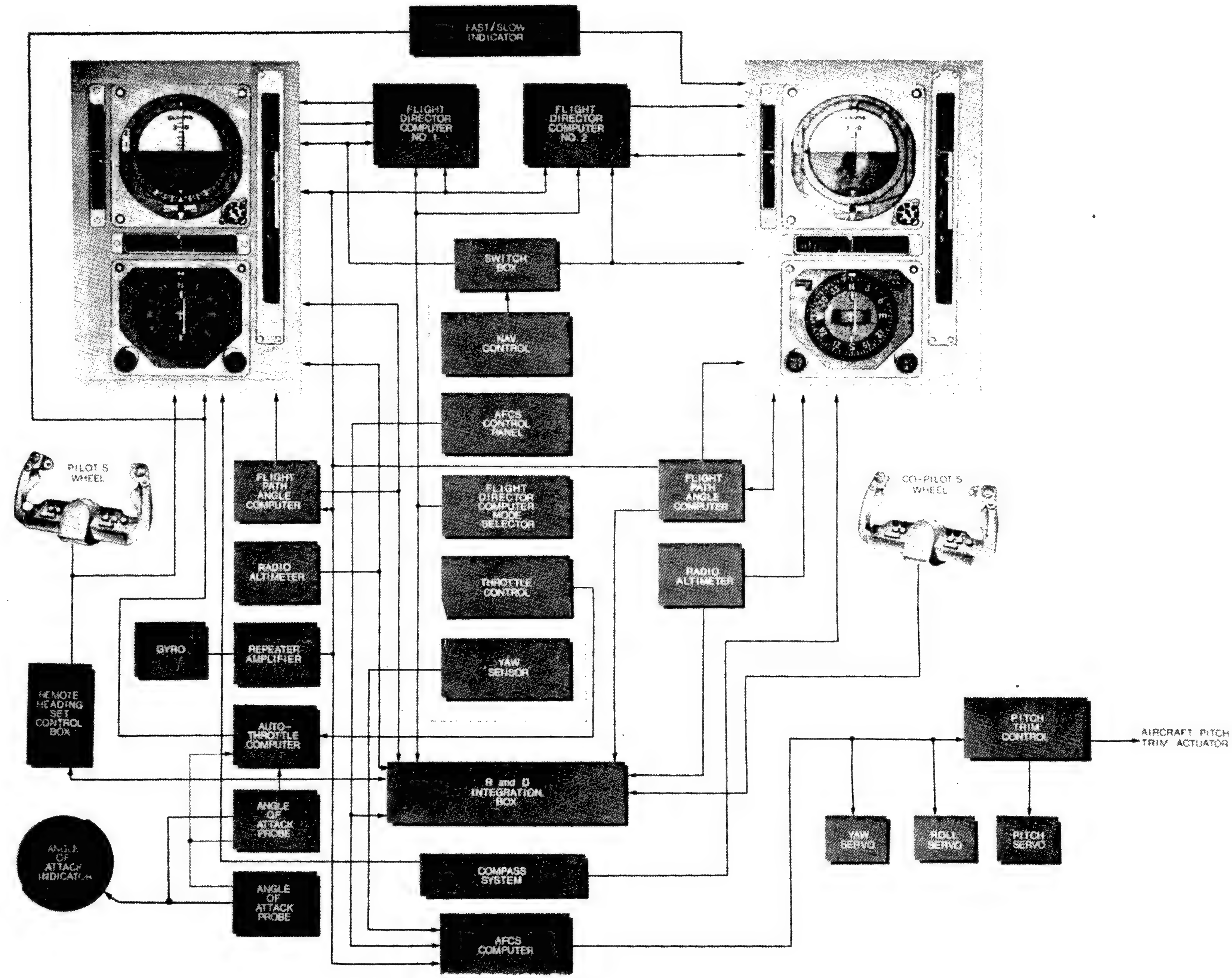


Fig. 14: Dual FDC Installation

to provide steering commands to the dual ADI's. Dual flight path angle computers, radio altimeters, and navigation (ILS) receivers were also installed.

Displays and computers are broken down into pilots and co-pilots, providing redundant displays of critical parameters. Signal switching circuits contained in the R&D integration boxes are selectable to command and/or display to either the pilot's or co-pilot's side. In addition to the redundant installations, a single three-axis Automatic Flight Control System is installed. The AFCS incorporates individually engageable axes and three axis force steering. In the test aircraft, dual force wheels and yaw force sensors were employed to provide either pilot with force steering capability.

A single angle of attack display system was installed providing a panel mounted indicator (pilot side) and an apexer (Fast/Slow Ind.) mounted on the glare shield and visible to either pilot or co-pilot. In conjunction with the angle of attack system, a single automatic throttle control system is used to maintain optimum throttle control of the adjustable reference provided by the angle of attack display system during approach and landing.

Representative photos of the panel displays (pilot and co-pilot) and the basic control console for selection and control of the dual navigation receivers, automatic throttles, flight

director selection and flight path angle selection are contained in Figures 15 and 16.

Fig. 15: Panel Display Pilotside

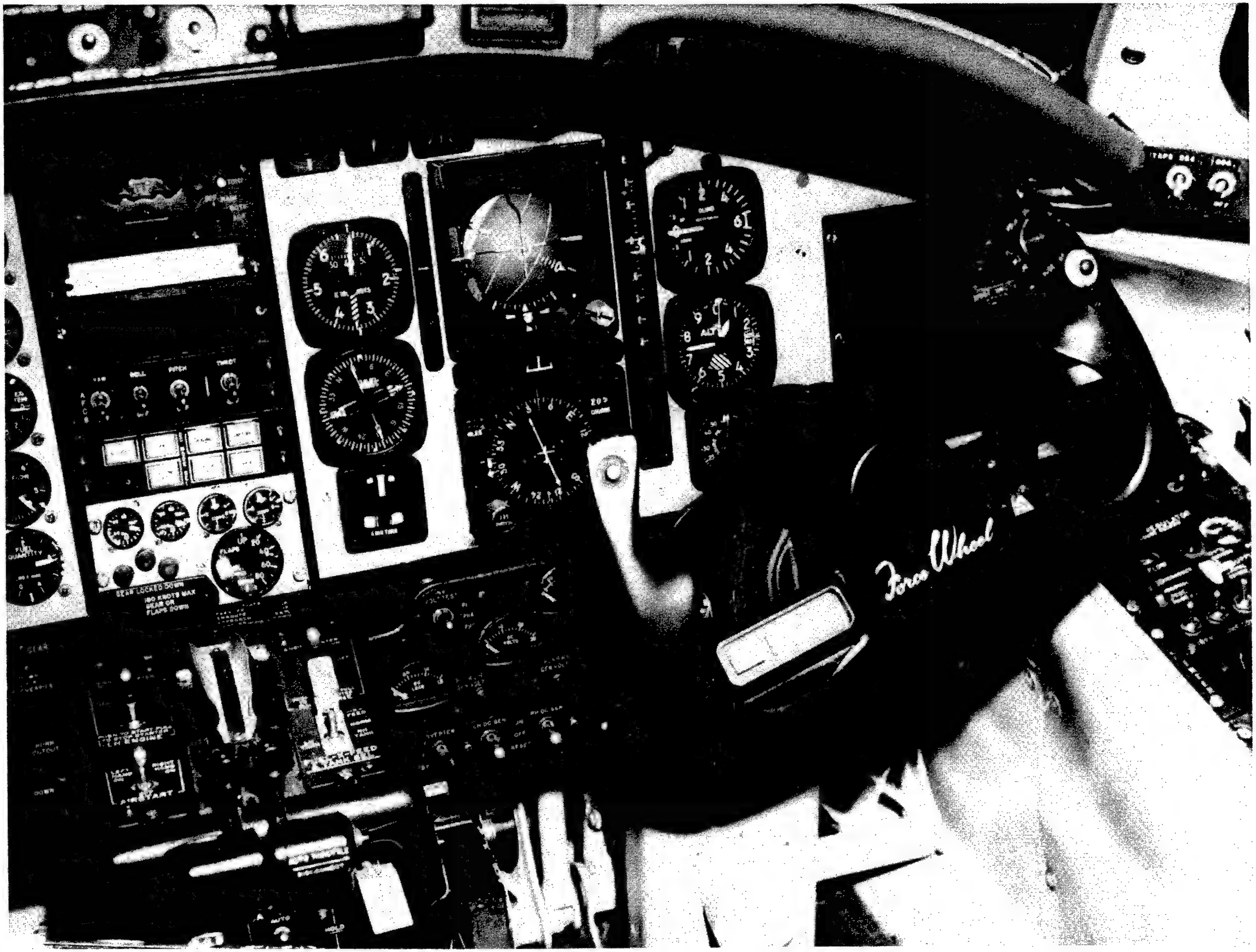


Fig. 16: Panel Display - Co-pilot Side

MODE SELECTION & ANNUNCIATION. The mode selection features, terminology, mechanization and annunciation of the experimental systems became of significant importance. Design effort was directed toward providing a versatile, integrated Flight Director/Automatic Flight Control system for the approach and landing phase. The following discussions defining the flight director systems employed in the test aircraft will encompass all circuitry required to perform the particular task, and will not be limited to the flight director computer alone. Further, to provide continuity of conceptual logic, the discussion will cover each mode or submode of operation available within the total system. It is pointed out that the basic flight director concept has not been altered in any form, and indeed, a great deal of effort was devoted to maintaining the steering command philosophy.

The flight director computers utilized were designed and configured to tailor their capabilities to the requirements of the approach and landing profiles. In addition, external circuits were fabricated and interfaced in order to provide the desired signal switching, scheduling, and shaping, as dictated by the requirements of the approach from the middle marker through flare, touchdown, and rollout. Full capability exists in the system to couple the automatic flight control system to the steering bar signals. In the following text the flight director modes shall be described in detail. However, it should be kept in mind that the steering commands

can be altered by the human pilot or by the AFCS, depending on whether or not the AFCS is coupled to the flight director system. More detailed discussion of AFCS utilization appears later in the text. See page III-69.

Basic lateral flight director mode selection was designated HEADING, CAPTURE and TRACK. The designations were related directly (and respectively) with the standard NAV. MANUAL, ILS NORMAL, and ILS APPROACH nomenclature. One important difference is noted between the Track and ILS Approach modes. The ILS Approach mode provides both lateral and longitudinal computations and resultant steering commands; the Track mode is confined to the lateral axis only and is commanded independent of the longitudinal axis. Thus, a lateral track complete with cross wind correction could be commanded at any time the localizer beam was captured without regard to the glide slope signal. In extreme cases, on a very close-in vector, it was actually possible to track the glide slope beam and still be capturing the localizer beam.

All three modes are truly lateral flight director modes and are described operationally as follows:

Heading - commanding this mode displays a lateral computation at the BSB, providing an optimum bank angle to maintain the aircraft heading selected on the heading set "bug" on the HSI. Aircraft bank angle is limited to ± 30° roll attitude; unique

circuits controlling the heading set feature are explained in greater detail on page III-49.

Capture - this mode is used to capture an ILS Localizer beam and utilizes a beam/course/bank ratio to establish its lateral computation at the BSB. Bank angle is limited to ± 30° roll attitude, and the beam/course ratio is further modifed to provide a 45° course cut to the beam with the maximum (± 150 MA) beam signal available. Normally, and for optimum performance, this mode is commanded approximately 8 miles from the approach end of the runway when the localizer error begins to decrease from its maximum of 2 dots deviation as displayed on the HSI.

Track - as described earlier, this is a mode selected to maintain a lateral track in the center of the localizer beam. Basically the lateral computation is similar to the capture mode, except that provisions are incorporated to compensate for any beam standoff resulting from a cross wind component.

In all cases cross wind correction is accomplished by altering the heading of the aircraft. Bank angle and beam error are null seeking; several methods are utilized to achieve this. In one case a beam error integral term was added to the computation; this assumed that any long-term beam error was the effect of a cross wind. Over a period of time a corresponding signal was developed which modified the aircraft

heading to compensate for cross wind drift. In the other cases, the raw runway heading signal (course) was modified by converting it into a course rate signal. See Figure 17. Thus, the course signal essentially became a damping term in the calculation, and the aircraft was allowed to establish the appropriate heading to maintain the beam error at null.

In the longitudinal axis, both independent modes and those that supplement the approach and landing phases were mechanized. The supplemental modes are in reality a series of annunciated sequences and were established to fulfill the requirements of the approach and landing profile. These sequences are used in the ILS approach and in the precision GCA approach. Only the ILS portion shall be covered at this time. The GCA portion is covered separately, beginning on Page III-52. The ILS landing mode/sequences, INITIAL, FINAL, 100 FT, and FLARE, are described as follows:

INITIAL - this sequence is normally initiated automatically during an ILS approach when the following conditions prevail: (1) localizer and glide slope flags retracted, indicating proper signals are being received, (2) localizer signal is less than $\pm$ 100 micro amperes, and (3) glide slope signal is within $\pm$ 10 micro amperes. Actuation of INITIAL will limit the bank angle to a maximum of 15° and release any prior longitudinal mode. If no prior longitudinal mode was selected and the initial sequence is actuated, the PSB will

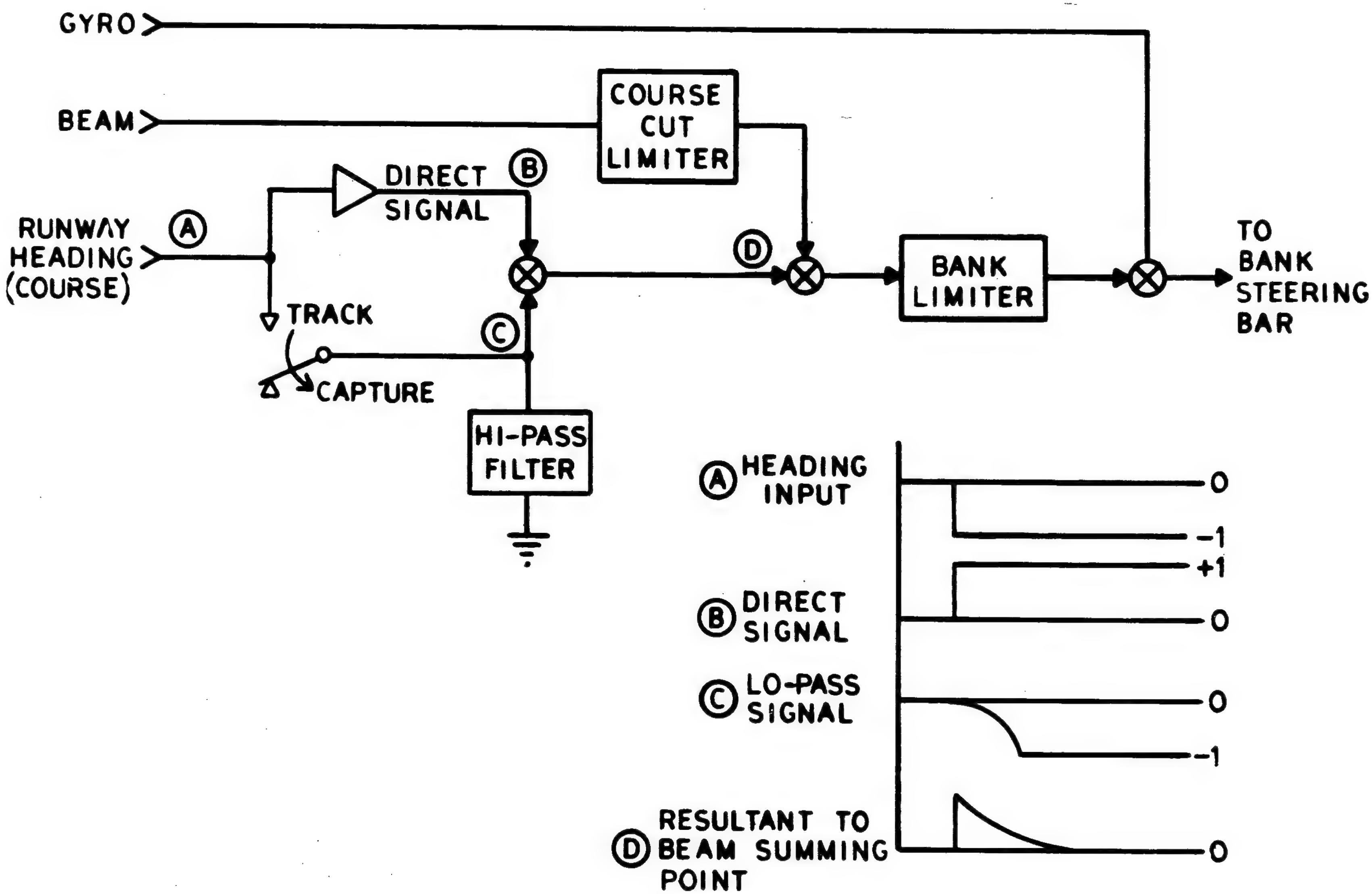


Fig. 17: FDC Cross-wind Filter

come into view and command a pitch-down for glide slope tracking. This sequence, as with all modes and sequences, can be manually commanded by depressing the appropriate buttons on the force wheel. In addition to establishing longitudinal tracking of the glide slope signal, the initial sequence is prerequisite to a continuing approach.

FINAL - once the initial mode has been established and tracking of the glide slope signal has been initiated, the middle marker beacon was used to initiate the FINAL sequence. At this point a 66% reduction in the glide slope signal gain was accomplished to compensate for the effect of beam convergence; also, a reduction in bank limits (laterally) from $\pm$ 15° to a nominal $\pm$ 8° roll attitude was established from this point to touchdown.

100 FT - an approach sequence initiated by the altitude signal from the radar altitude system. The 110 ft. trip fades out the glide slope signal to the flight director computer and fades in the flight path angle reference signal for the longitudinal computation. The "fade out" of the glide slope signal and the "fade in" of the flight path angle reference signal occurs linearly over a 5 second (nominal) interval. Since most ILS glide slopes are nominally 3° or less, a flight path angle reference of minus 2.8° was established as being nominal and resulted in an actual glide path fairly consistent with the normal initial GS angle associated with the ILS Glide

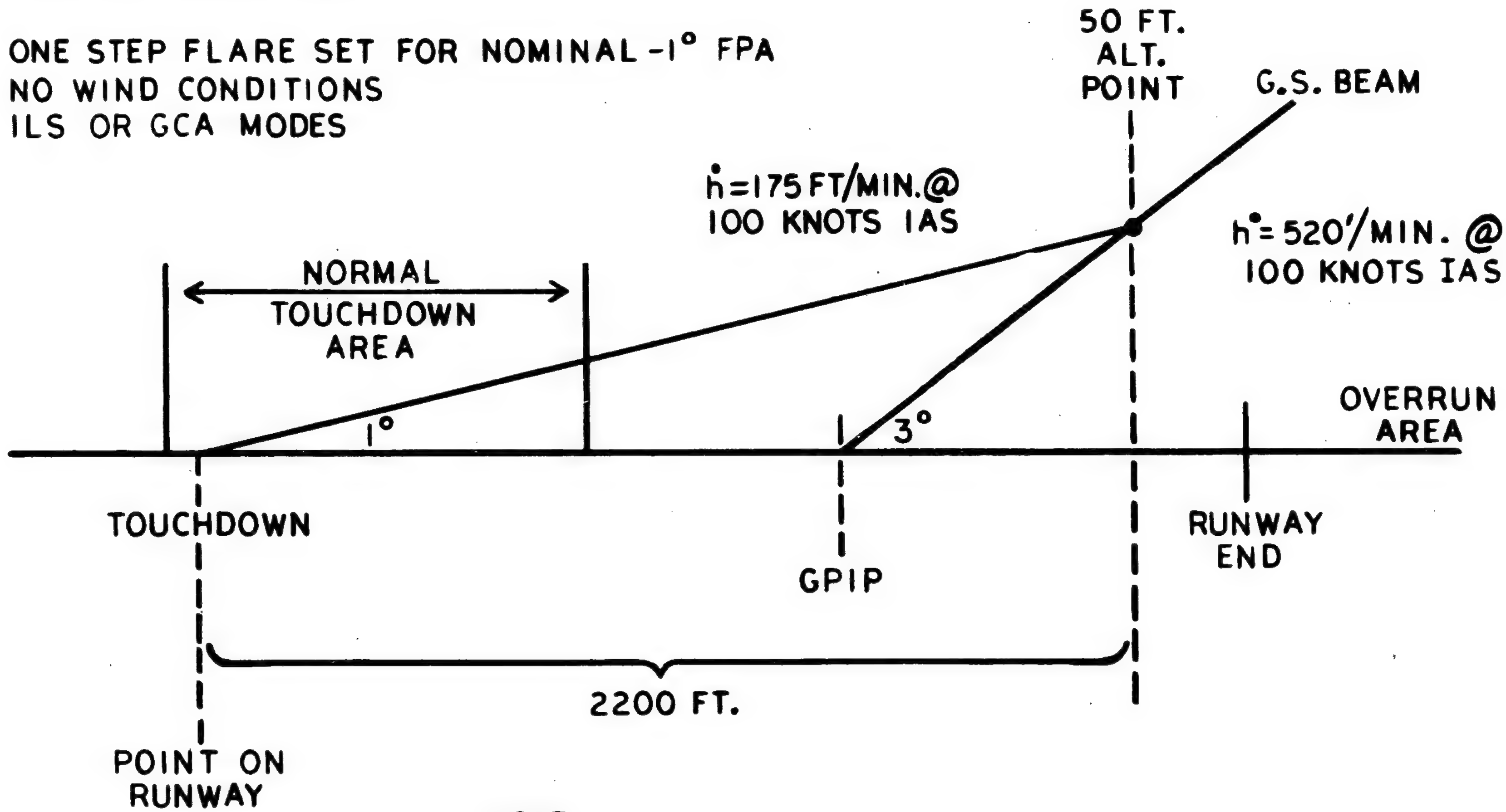
Slope. This composite therefore resulted in positive control of the longitudinal axis during the glide slope extension required to bring the aircraft from 100 ft. absolute altitude to the point of flare.

FLARE - initiated by the radio altimeter at 50 ft. absolute altitude, which was chosen as a nominal flare point. This approach sequence referenced the longitudinal computation from the minus 2.8° FPA established between 110 ft. and 50 ft. absolute altitude, to a preset flight path angle which established the transistion from the glide slope rate of descent (600 ft.-700 ft./min. for a T39) to a comfortable touchdown rate of descent (200ft./min. for a T39.) The transition was accomplished in two similar methods. One employed a "One Step Flare" and was a direct transition from the minus 2.8° FPA to a minus .9° FPA commanded as a step function at 50 ft. absolute altitude. (See Figure 18). The other method utilized a "Two Step Flare" for comparative purposes. (See Figure 19). The first step occurred at 50 ft. absolute altitude as above, but transitioned to a slightly higher FPA reference of minus 1.8°; at 19 ft. + 0/-3 absolute altitude the reference was further reduced to minus .9° FPA. In addition, the second step logic was utilized to command throttle retard to idle, if the auto throttles were engaged.

The independent modes also displayed as longitudinal computations are altitude hold and flight path angle. These

LANDING SITUATION

ONE STEP FLARE SET FOR NOMINAL -1° FPA
NO WIND CONDITIONS
ILS OR GCA MODES



NOTE:
IN ACTUAL OPERATION, ALTITUDE LOST IN TRANSITION FROM -3° TO -1° γ PLUS ANY HEADWIND COMPONENT RESULTS IN A TOUCHDOWN PRIOR TO TOUCHDOWN POINT ILLUSTRATED.

Fig. 18: One Step Flare Profile

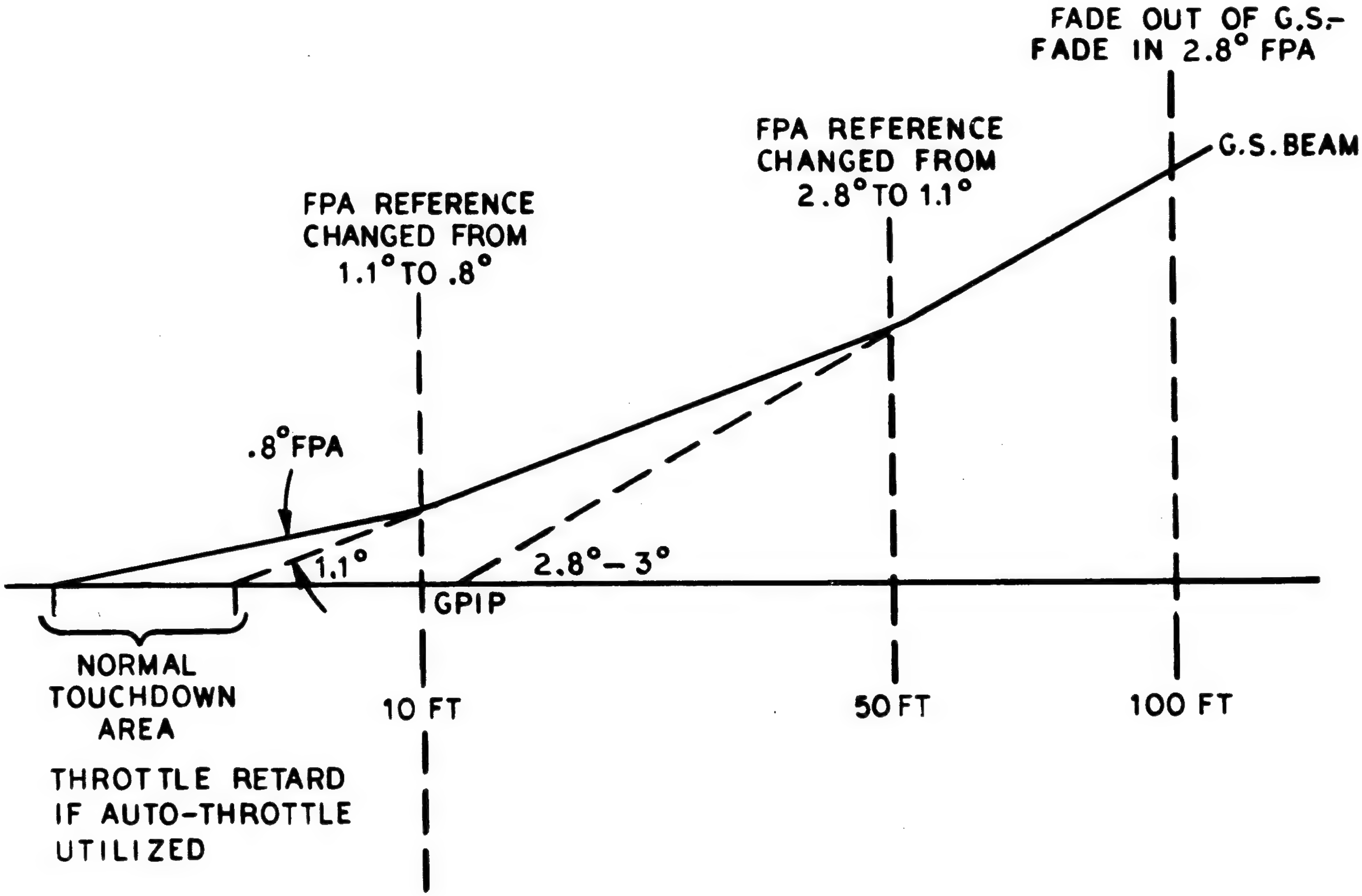


Fig. 19: Two Step Flare Profile

modes are described below:

ALTITUDE HOLD - selecting this mode references the longitudinal computation to the altitude held at the time the mode was commanded. Due to the type of altitude sensor utilized, it was necessary to release the mode if a change in altitude was desired, then manually fly to the new altitude and re-engage the mode. In two aircraft the altitude hold function was not included as a flight director function, but remained an "Auto Pilot Function" which was useable only if the AFCS pitch axis was engaged. In this case, if a change was desired in altitude, it also required releasing the mode, then re-selecting the mode when the new altitude was established. The altitude hold function was especially useful following penetration and holding the final altitude required to intercept the glide slope signal at a point near the outer-marker.

FLIGHT PATH ANGLE - in addition to providing the "Glide Slope Extension" (110 ft. to 50 ft. absolute altitude) and the aircraft flare reference, this reference is utilized as a primary control parameter in the longitudinal computation whenever the mode is selected. Facilities for selection of a specific flight path angle through a ± 20° range were included in all four aircraft.

YAW GROUND CONTROL - this sequence is automatically commanded

when wheel strut compression occurs, after the flare sequence and landing is committed. (See Figure 20.) The sequence enables the necessary circuitry to control the rollout of the aircraft laterally along the runway utilizing the localizer beam and runway heading as the primary signals in the lateral computations. It reduces the longitudinal computation to zero, synchronizes the AFCS pitch axis, if engaged, and returns the aircraft stabilizer trim system to the takeoff position. Thus, during this sequence the aircraft is not only controlled laterally, but is readied for takeoff if a go-around should be required.

GO-AROUND - due to the fact that this mode is commanded as a result of an unsatisfactory approach and/or landing, or request of ground controllers, it has precedence and will preempt any mode or sequence that had previously been selected or displayed. It can be commanded at any time in the air or after touchdown. Commanding "Go-Around" during an approach provides for full throttle advancement (with auto throttle), a wings level command laterally (or stowing the BSB and maintaining 0° roll angle with the ADI sphere), and a longitudinal computation (using angle of attack and acceleration as primary references) which provides the pitch attitude for optimum climb performance at whatever airspeed the mode was commanded. If the mode is commanded on the runway, the lateral computation of yaw ground control is displayed on the BSB until the aircraft lifts off; the lateral display will then

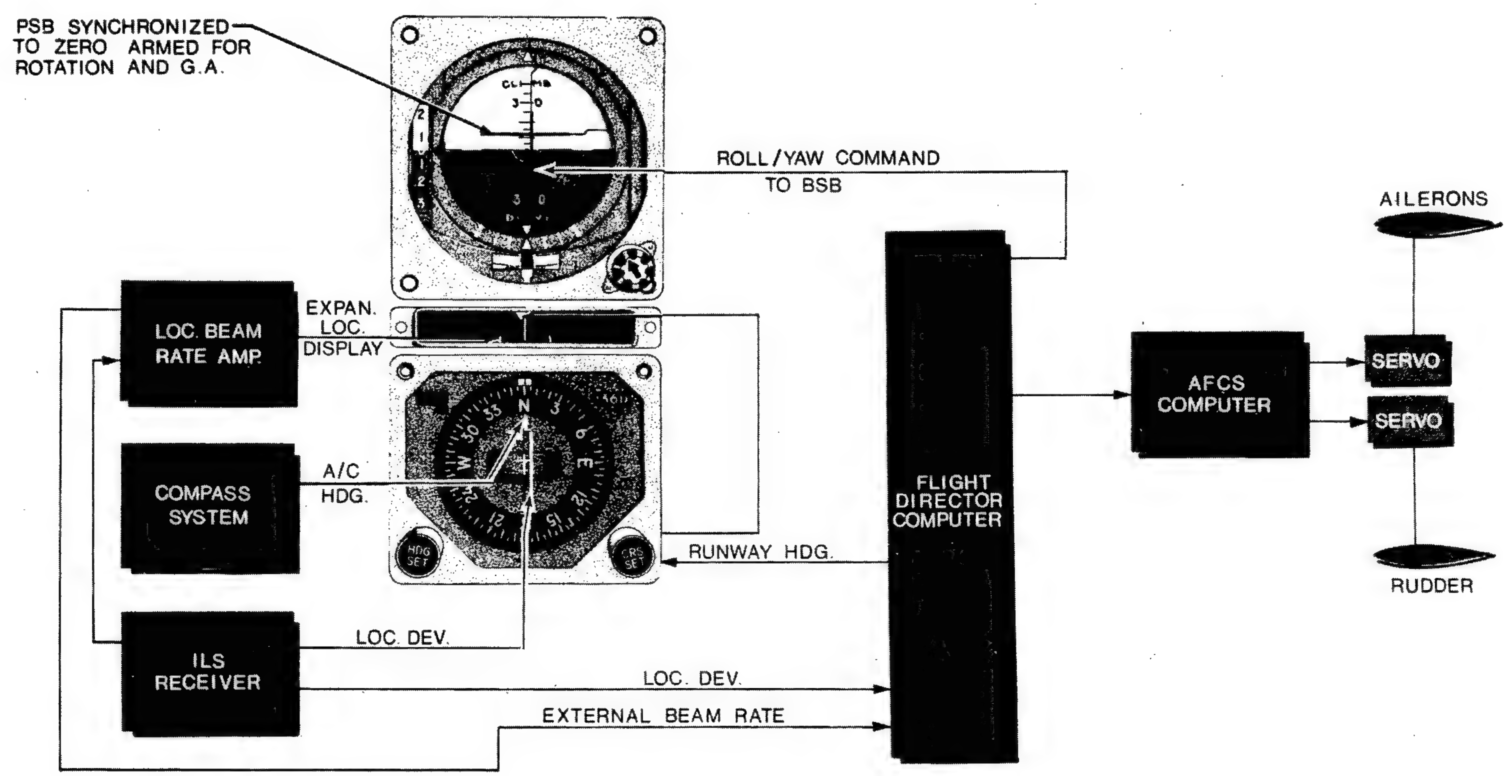


Fig. 20: Yaw Ground Control Block Diagram

revert to that described earlier. (See Figures 21 and 22).

An additional sub-mode, a lateral steering computation termed "Side Slip" was investigated. (See Figure 23). The concept was mechanized to evaluate the feasibility of eliminating the aircraft's crab angle to the runway (normally due to the cross wind component encountered during an approach) and at the same time minimize or eliminate any cross track (drift) generated by the "de-crab" manuever. The de-crab was accomplished by commanding sufficient rudder to align the aircraft with the runway heading. The runway alignment or course error was displayed on the Lateral Situation Indicator in expanded form; rudder command was generated (either manually or automatically) to maintain a zero course error on the indicator.

To eliminate the cross track generated by the de-crab manuever, the heading change resulting from this manuever was sampled and added to the lateral computation as a bank command to bank the aircraft into the wind. Upon completion of both commands, a forward slip is established whereby the aircraft is aligned with the runway and the ground track is still aligned with the localizer beam since any drift was cancelled thru the bank manuever. To accommodate changing wind conditions which would require different bank angles, an integral of localizer beam error and localizer beam rate was added to the initial bank command established from the de-crab manuever.

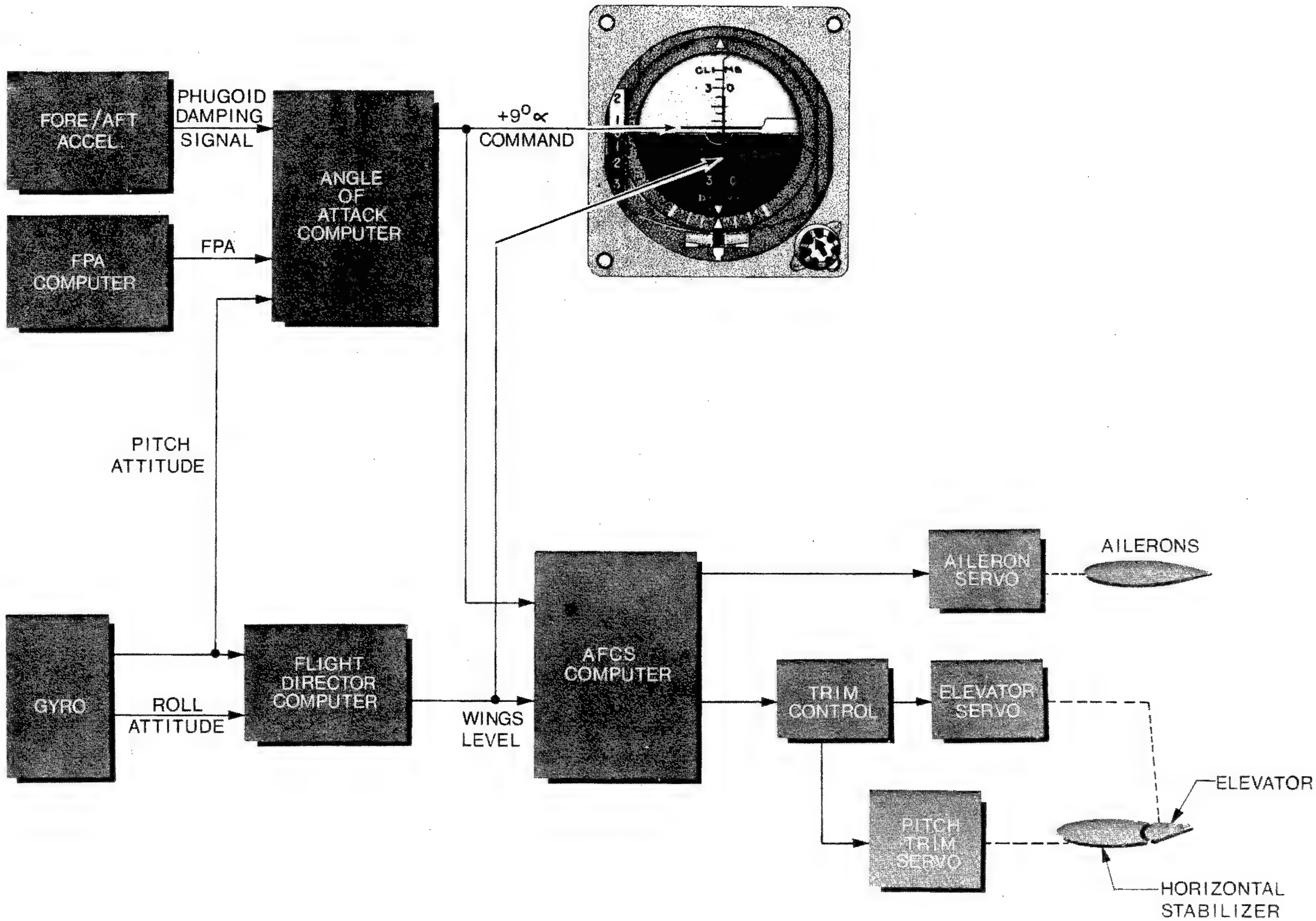


Fig. 21: Rotate and Go Around Block Diagram

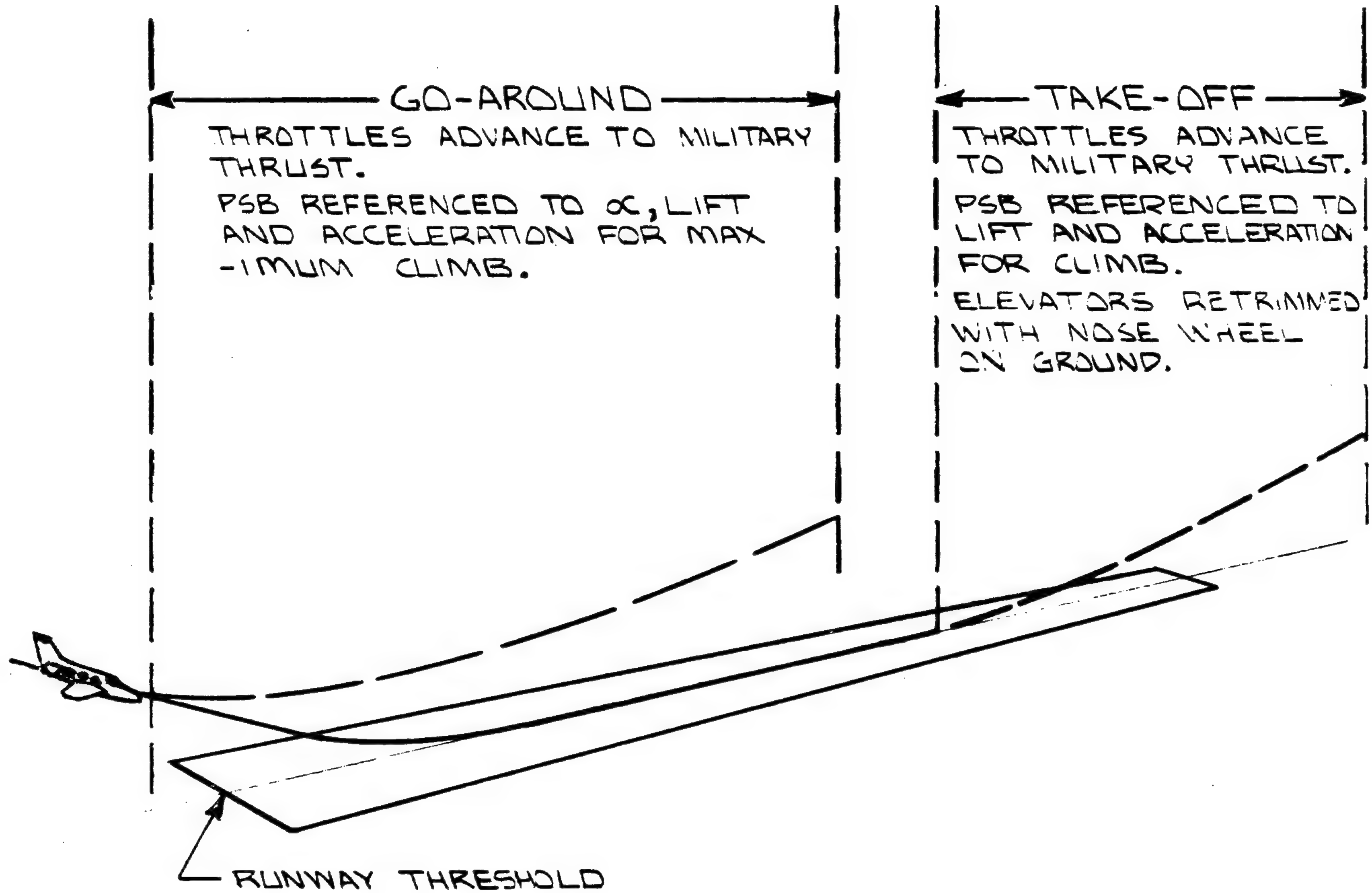


Fig. 22: SCAT Take-off and Go-around Profile

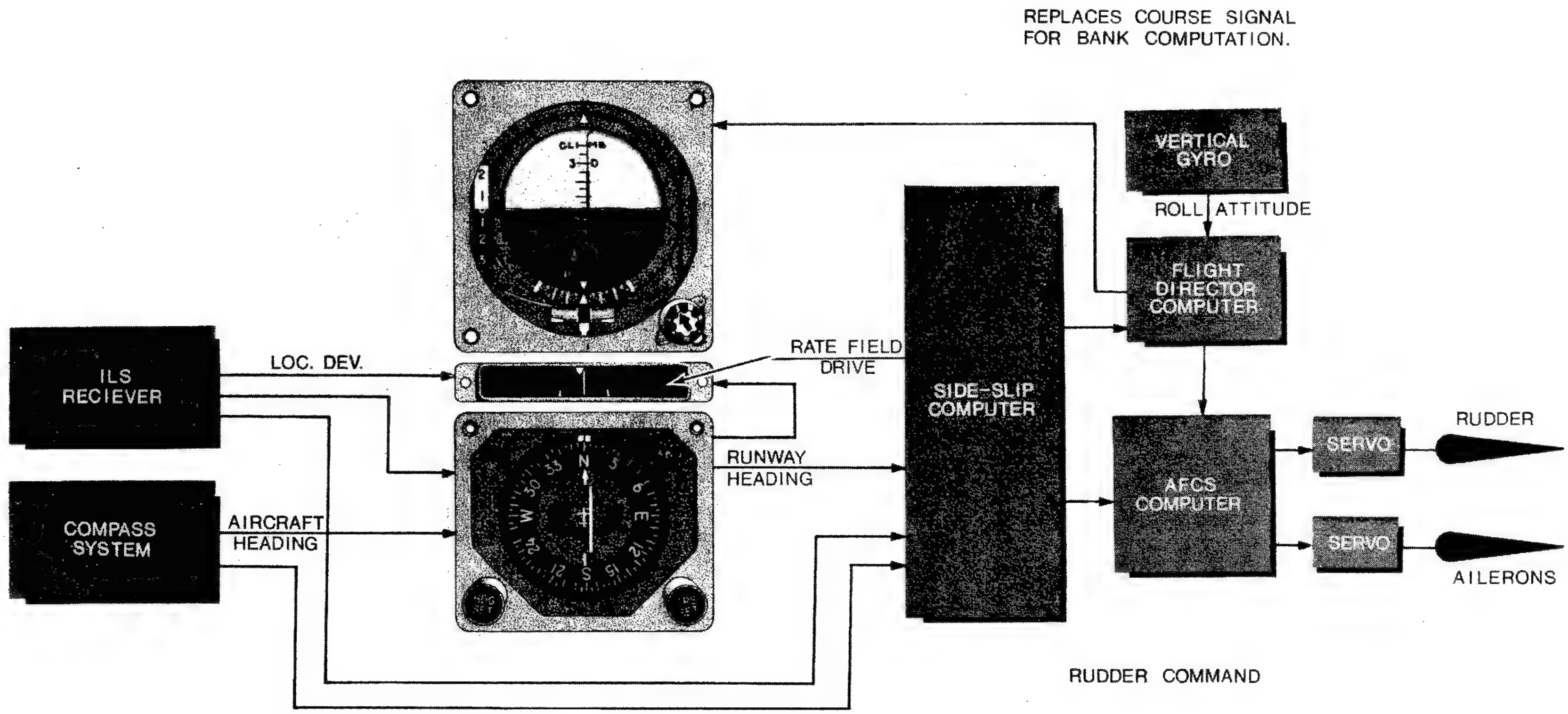


Fig. 23: Side Slip

Side Slip is initiated at the middle marker when the FINAL logic is introduced. This assures that transition to the sideslip configuration is completed at a comparatively safe altitude, and the requirement for a last-second manuever at a very low altitude is negated. Side slip progress and accuracy is displayed on the Lateral Situation Indicator, cross track position error with the miniature runway and cross track error rate with the moving rate field.

Evaluation of the side slip circuits is incomplete as of this writing, primarily due to the state of the art electronics available at the time the internally developed computer was fabricated. Present day state of the art electronics remove this obstacle, simplify the design requirement and assure the precision and reliability required to continue the evaluation.

The Landing Sequence Indicator is of major importance during the approach and landing phase. (See Figure 24). This indicator

Fig. 24: Landing Sequence Indicator

is used as a visual cue of the approach progress, altitude

check point, and a verification that changes in system logic circuits have been accomplished. The "bars" illuminate as a function of their terminology, ie: The outer marker beacon signal illuminates the OM bar, the middle marker beacon signal illuminates the MM bar, and the absolute altitude signal from the radio altimeter illuminates the 100 and 50 bars at their respective altitudes. At each check point the circular lamp at the far right would flash approximately five times to focus attention that a check point has been passed.

The "blocks" are utilized to indicate the sequence status of the landing system, and illuminate as a result of the required logic circuits having been tripped. For example, the initial block will illuminate only when the glide slope center trip circuits are enabled, ± 15° bank angle limit circuits enabled, etc. Thus, each block indicates that the required system status has been achieved at the required check point. The shaded area at the lower left is illuminated at any time the aircraft wheel struts are compressed and the appropriate Yaw Ground Control circuits activated. The Go-Around block is self-explanatory; it illuminates whenever the mode is selected and the necessary circuits activated. The indication flashes continuously at approximately 1 cycle per second at any altitude less than 100 ft.; above 100 ft. the indication is constant.

The overall result of the preceding discussion evolves into

the ILS Profile, shown graphically in Figure 25. It was broken into arbitrary segments labeled, in order of their appearance, Capture, Track, Initial, Final, 100 ft., Flare, Roll-Out, and Go-Around. Events which signalled the onset of each segment provided a switching function, in many instances automatic, and an annunciation on an instrument installed above the Attitude Director Indicator.

Bank limiting was applied for the capture mode which was used to acquire the localizer beam center. Beam center acquisition was recognized by the pilot who then selected the Track mode. A reduced bank limit and increased BSB sensitivity were applied. The wash-out filter on the course deviation signal permitted the aircraft to set up a crab for cross-wind compensation.

Interception of the center of the glide slope beam, which occurs at the outer-marker for standard approach altitude, provided an automatic switching function which put the Pitch Steering Bar into use. Altitude Hold, if engaged, was disengaged and a short-term pitch down signal to initiate descent appeared on the PSB. Pitch signal during the initial mode was a mix of glide slope deviation with pitch attitude applied as a term with a fourteen second wash-out. A small amount of pitch attitude rate was applied as a damping term.

Passage of the middle-marker beacon provided another automatic

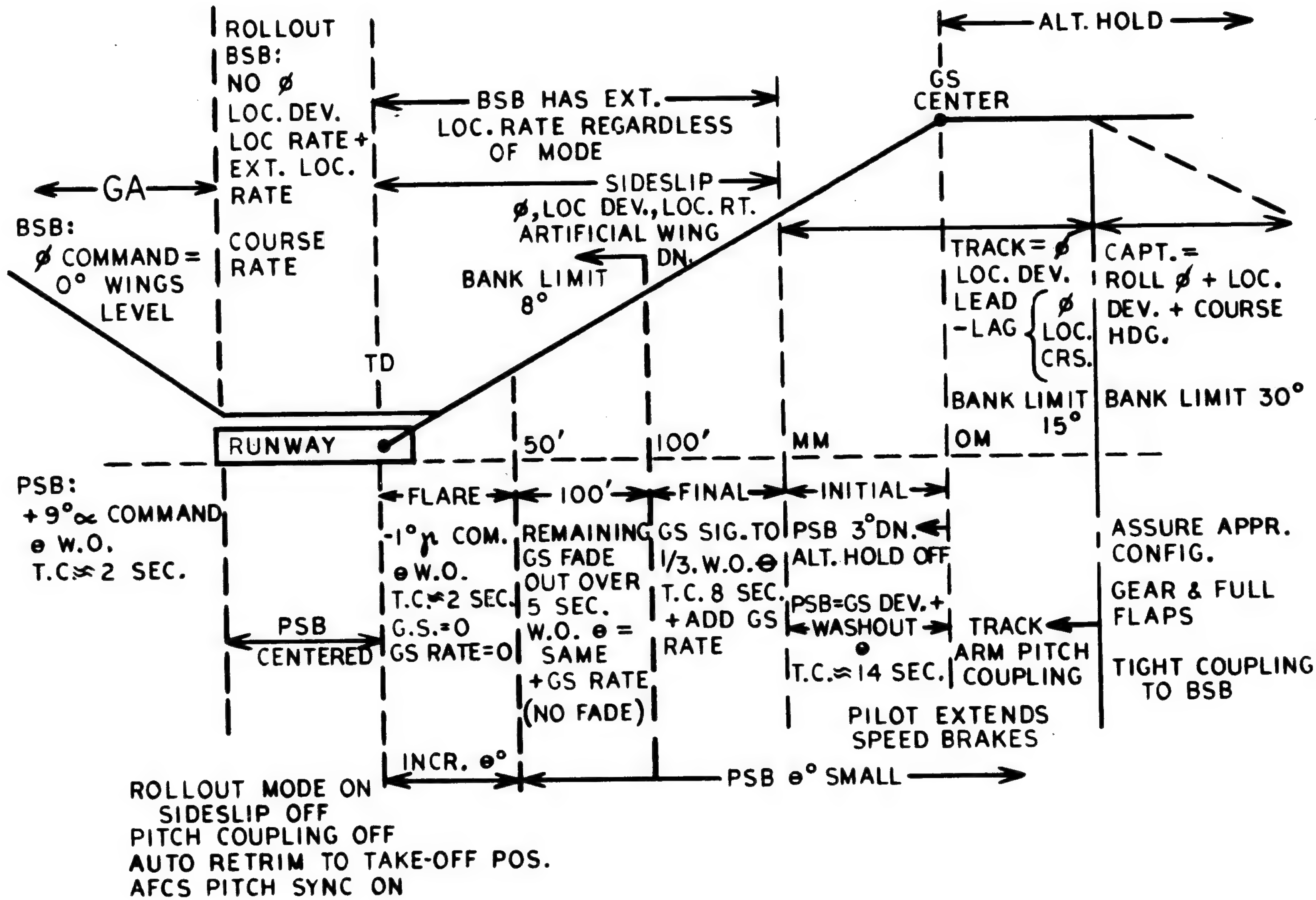


Fig. 25: ILS Profile

event switching. At this time additional localizer rate signal, developed outside the flight director computer, was added to the localizer deviation signal on the bank steering computation for control in the FINAL segment.

The Side Slip mode, when used, was initiated at final. Any crab, which appears as a runway heading error, was applied to the yaw axis to return the aircraft to the runway heading, and a proportional signal applied to the roll axis directed a wing-down to prevent a lateral drift.

The glide slope signal at commencement of the final segment was reduced to 33% of its value to compensate for the effect of convergence. Pitch attitude time constant was reduced to eight seconds, and a glide slope rate term was added for damping.

The 100-foot absolute altitude event was sensed by the radar altimeter and the 100-foot segment changes were automatically switched on. The remaining glide slope signal was faded out over a five-second interval, and the bank limit was further reduced to eight degrees. A flight path angle signal became the reference for the pitch axis as the glide slope signal was removed. This signal, with altitude rate supplied by the radar altimeter, was used to provide a reference for the flare mode.

Flare was automatically signalled by the 50 ft. (selectable) absolute altitude event. A nominal one-degree down path angle was commanded, the pitch attitude wash-out time constant was reduced to two seconds, and the pitch attitude rate damping was increased.

At touch-down, the pitch steering bar was allowed to go to null (centered) position. A wings-level (simulated attitude) signal was applied to the autopilot roll axis, but the bank steering bar remained active as lateral control was switched to the yaw axis.

During roll-out, the command signal on the BSB was provided by a mix of localizer deviation, localizer rate and an additionally imposed, externally developed localizer rate. An automatic repositioning of the horizontal stabilizer to take-off trim was provided.

A go-around command, initiated by the pilot, put roll attitude (gyro wings-level) on the BSB and an alpha (angle-of-attack) command of nine-degrees up (selectable) on the PSB. The two-second pitch attitude wash-out was reapplied. With auto-throttle, this command called for automatic throttle advance to take-off power. Go-around could be commanded before touch-down and took precedence over the existing mode.

TALAR and STATE landing systems utilized the same type of

guidance as the ILS mode. These systems used new radio beam transmitters that were more portable and had application to a tactical environment.

The Advanced Integrated Landing System (AILS) used a scanning type radio transmission. Those portions of the scanning beam, coded as to azimuth, elevation angle, and DME were received by the aircraft as they applied to its angular elevation from the landing site. The horizontal approach path was scaled into increments called "Base Lines". The length of the base lines was selectively variable to provide for variation in the intercept point on the runway.

The AILS equipment was used in the Final Approach Profile Investigation flight test program. The AILS ground installation at NAFEC, Atlantic City, New Jersey, consists of two permanent stations, one for elevation, located on the right side of the runway and 2500 feet inside of the threshold. The other station for azimuth and DME were located on the centerline at the stop end of the runway. The system uses a microwave scanning beam technique to transmit a code containing angular and distance information.

The airborne equipment as installed in the flight test aircraft was comprised of the R.F.Head (Receiver - DME Transmitter), the Range Angle Tracker (signal processor), and the Tacland/AILS Approach/Flare Controller.

The angular and distance information is received and processed by the airborne equipment, and thus determines the aircraft position with respect to the runway. This position is then compared to the programmed flight path in the Approach Flare Controller. Deviations of the aircraft from the programmed flight path are used to provide a parameter suitable for display on the steering bars of the ADI and/or for coupling to the autopilot.

Figure 26 illustrates the dual angle profile used in this Final Approach Profile Investigation program. The profile was determined by the airborne controller/computer and has four selectable GPIP's (Glide Path Intercept Point). These points are as follows; the distance of the GPIP's to the elevation site (EL) are referred to as BASELINES (BL):

1. 1500'BL - 1500 ft. from EL Site (GPIP 1000 ft. inside threshold)
2. 2000'BL - 2000 ft. from EL Site (GPIP 500 ft. inside threshold)
3. 2500'BL - 2500 ft. from EL Site (GPIP at threshold)
4. 3000'BL - 3000 ft. from EL Site (GPIP 500 ft. outside threshold)

The glide slope angles were also adjustable as indicated in Figure 26. Events which occurred along the profile, such as transition from one glide slope to another, flare, are also illustrated. Each of these events takes place at a fixed number of baselines, but at a different DME range according to the particular BL being flown.

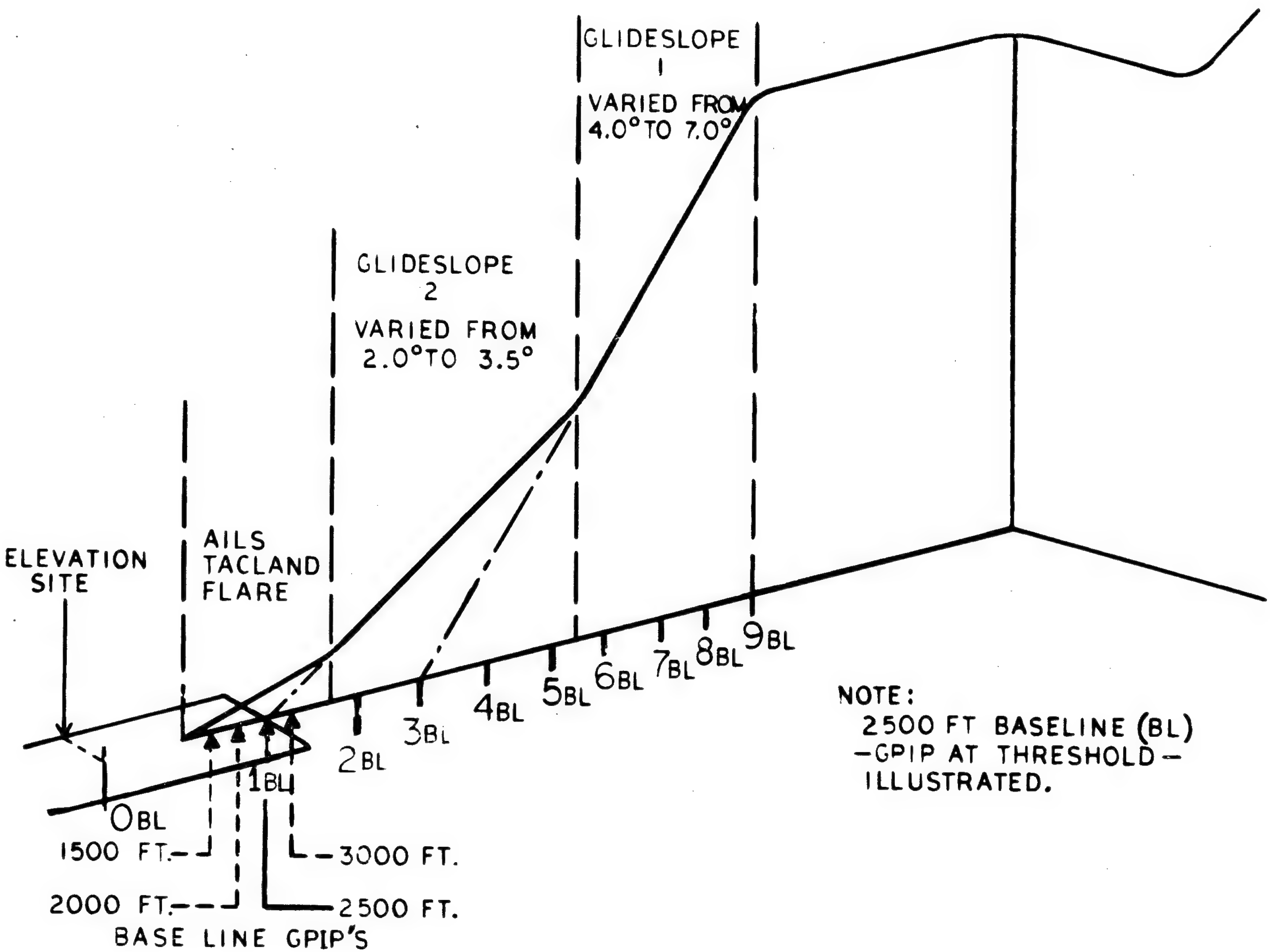


Fig. 26: AILS Dual Glideslope Profile

Though not considered modes or sequences, several unique functions deserve mention under the heading "Flight Director Mode Selection and Annunciation". The first is the Remote Heading Set circuits, which provide the pilot with the capability of incrementally but precisely repositioning his Heading Set function remotely.

The horizontal situation indicator, type AQU-4/A contains a heading command servo loop. This circuitry is, in effect, a high gain servo loop which, when provided with proper electrical information, will reposition the heading marker. In this concept the requirement for reaching over the control wheel to manually adjust the heading set knob on the HSI was eliminated and a remote electrical circuit was fabricated. The circuits providing this feature are termed the Remote Heading Set circuits, (see Figure 27), comprised of the following units: a switch located on the pilot's control wheel to provide a heading left/heading right logic; (+ 28 Volts was used as the logic voltage in this case.) a synchro transmitter properly excited with the HSI reference phase to provide the 3 wire 360° electrical information to the HSI heading command servo loop, and a means to precisely position the synchro transmitter in discrete steps and/or to "slew" the transmitter at approximately 25°/second.

Two methods of mechanization were employed (each with some

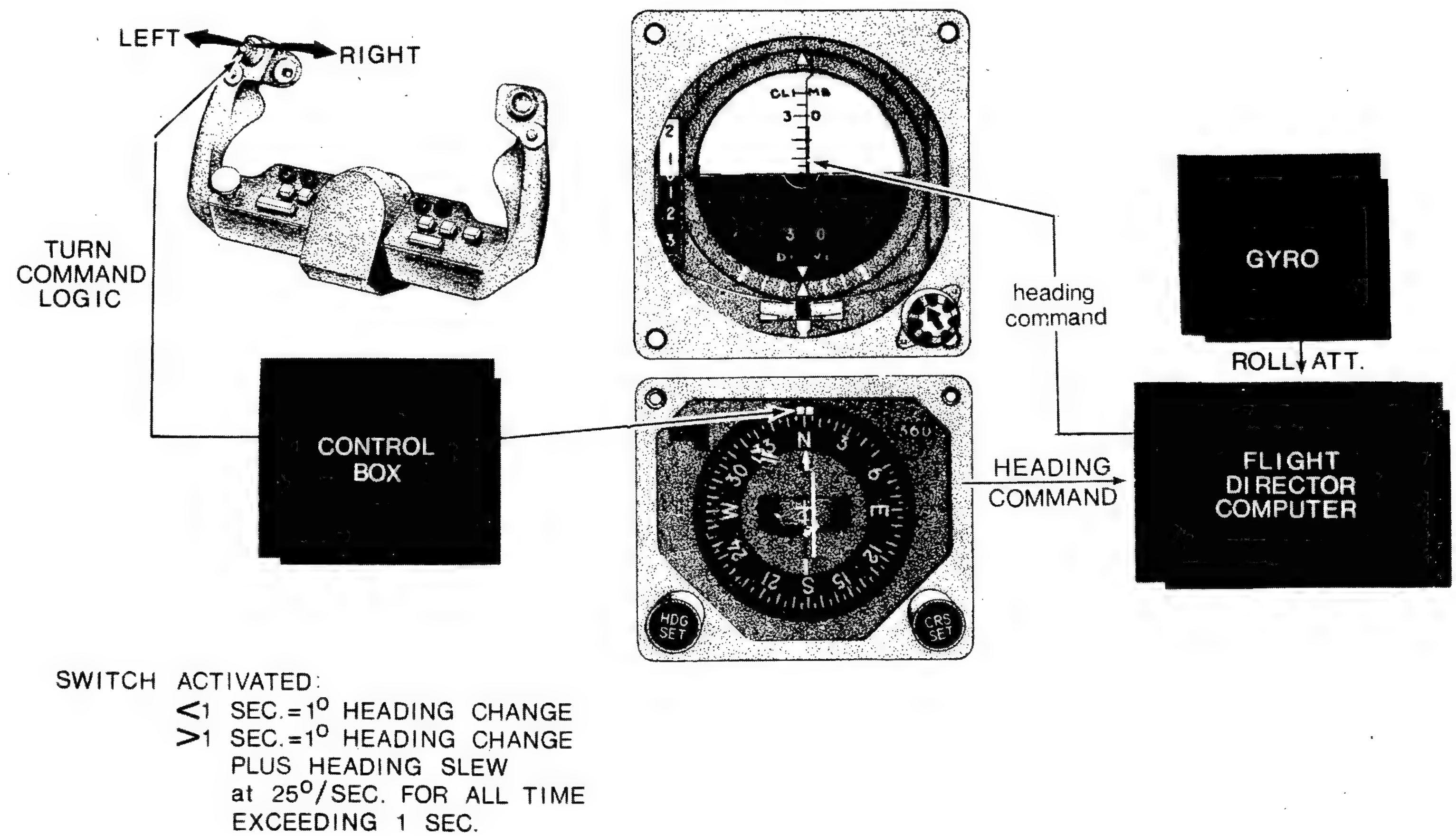


Fig. 27: Remote Heading Set

advantages) but both, in theory, are identical. Each provided precision timer circuits to obtain an incremental but precise 1° change in the heading set position, and after a suitable time delay would "slew" the heading marker at approximately 25°/second.

Functionally, the remote heading set circuitry operates as follows: The pilot, through actuation of the left/right remote heading switch on the control wheel applies +28 volts to logic relays in the control unit. The instantaneous 1° step and the resultant heading command occurs in less than 50 milliseconds. The slew circuit is enabled immediately, but is blocked out by a time delay circuit. The direction of the step is dictated by actuating the switch in the direction of heading change desired. By momentarily pressing and releasing ("beeping") the remote heading switch, the pilot can change the selected heading in precise 1° increments with no limit to the number of steps. If it is the pilot's desire to make a large heading change, where a slew is more appropriate, he can maintain pressure on the remote heading switch. After the initial step and a suitable time delay, a precision time circuit enables the slew circuits which results in the Heading Marker on the HSI being repositioned at 25°/second for as long as the switch is held actuated. Releasing the switch immediately resets the circuit.

One additional safe-guard is employed in both circuits. This

is the 100 ft. absolute altitude interlock. The requirement of this interlock is covered in the description of the GCA Mode, page III-52. During a precision GCA to low altitudes, a trip circuit disables the pulser unit, preventing an accidental slew, due to pilot pressure on the remote heading switch or a malfunction in the circuitry. Capability of the circuit below 100 ft. absolute altitude (detected by the radar altimeter aboard the aircraft) is limited to single 1° steps since a slew at this altitude would be very undesirable.

Acceptance of the remote heading set feature was practically universal among the pilots once sufficient familiarity and confidence was obtained. This was usually accomplished after several approaches and landings.

Three remaining operational procedures complete the lateral and longitudinal flight director mode selection and/or sequence discussion. These are Gound Controlled Approach, Yaw Ground Control, and Go Around, and are described as follows.

One of the most difficult approaches required of a pilot is the Precision Ground Controlled Approach (GCA) under minimum weather conditions. Flying instruments is exacting at best; however, to fly an aircraft on instruments at a ground controller's direction down a converging approach window, is

extremely difficult. A GCA Mode Approach Profile is depicted in Figure 28 for reference.

During the final phases of a typical GCA, the pilot is invariably required to make small but discreet heading changes commanded by the GCA operators. The number of heading changes is extremely variable, and in fact, is due to variables such as changing wind conditions, capability of the GCA operators, preciseness of pilot response, etc.

Presently, for every heading change directed by the GCA Operator, the pilot must respond, bank the aircraft at some angle to change the heading, then relevel the aircraft when the required heading is attained. A large percentage of his time during this manuever is now diverted from other critical control parameters such as rate of descent, airspeed, altitude, etc. Simultaneously, corrections to this vertical profile (Glide Path) must be responded to in order to maintain a position in space relative to the angle of the particular GCA glide slope. Corrections are made to vertical errors in number of feet above and below the Glide Slope. It is not uncommon for the pilot to "oscillate" about the Glide Slope, even though aware of the inherent lags in the altimeter and rate of climb instruments which in themselves tend to induce overshoots. Establishing a constant rate of descent to establish and maintain a constant glide slope under the best of conditions takes a unique skill and experience. When turbulence, windshears and changing airspeed are introduced,

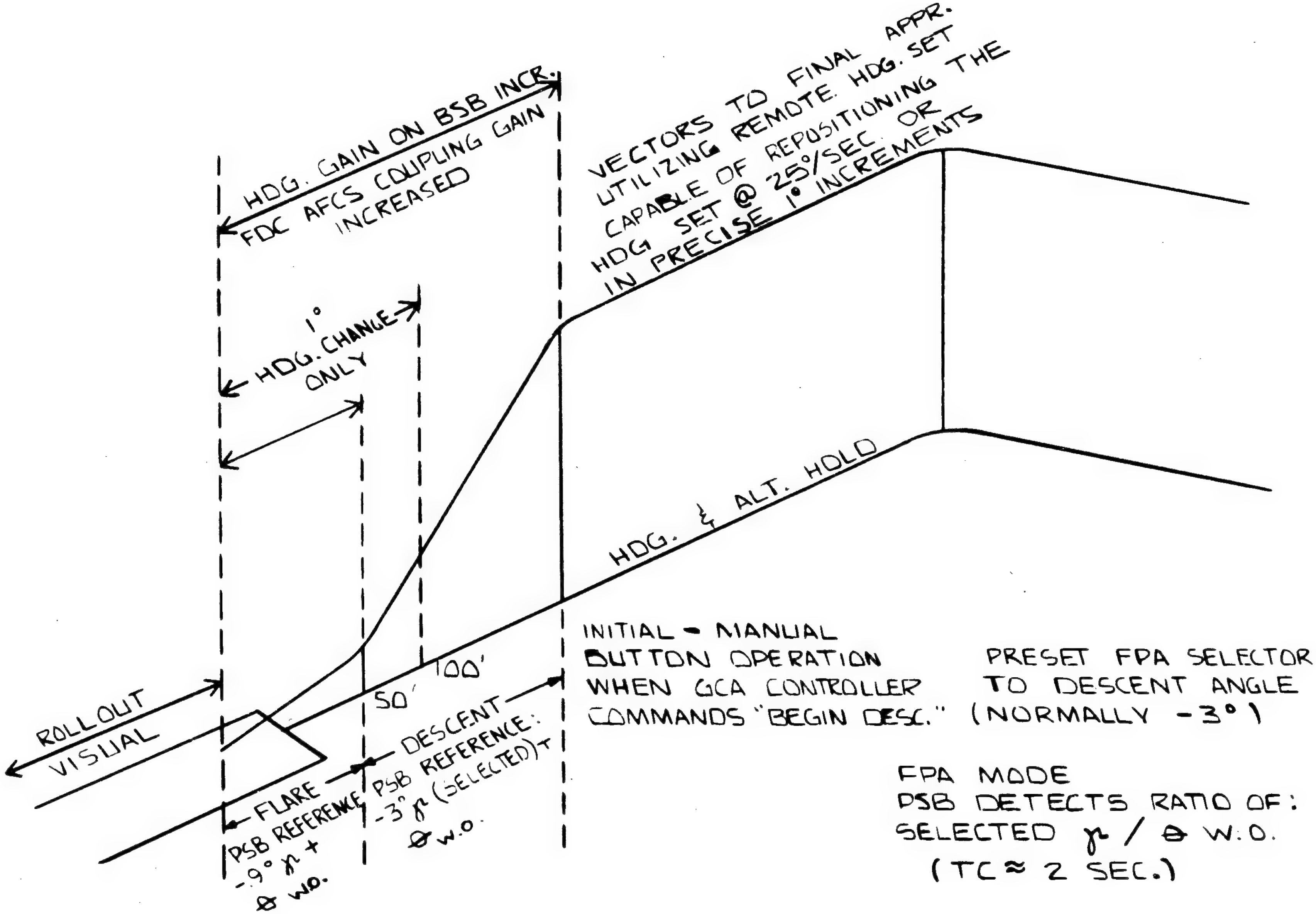


Fig. 28: GCA Mode Profile

the task approaches the impossible.

It is toward minimizing the pilot's workload that the concept of GCA mode was conceived. It introduces precision while diminishing the workload, thus reducing dependence upon skill and experience. The mode has been successfully demonstrated to and flown by pilots inexperienced in jet aircraft or GCA procedures time and time again. The response has always been enthusiastic, with an order of magnitude increase in performance skill.

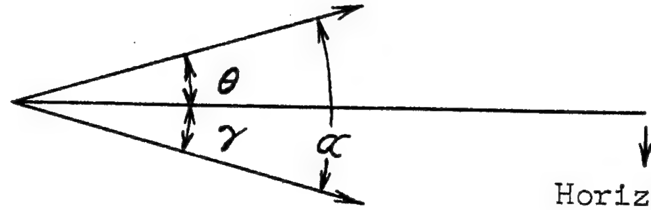
The basic concept for the GCA mode is to provide flight director steering information of sufficient preciseness to enable the pilot to make the required corrections in the lateral and longitudinal axes simply and efficiently, but with a great deal of accuracy. This required establishing adequate parameters to be displayed as steering information to the pilot. In addition, the pilot must have the capability to make discreet but precise alterations to the parameters utilized in order to respond instantly to the GCA operator's commands. Last, the parameters are also displayed in raw form so that the pilot can constantly cross-check his input to the resultant change in flight path.

In the lateral axis, heading is displayed on the bank steering bar and used to maintain a precise lateral ground track. Heading corrections are made utilizing the remote heading set circuitry described earlier. Thus, with the movement of

the L-R remote heading switch on the control wheel, instantaneous and precise heading changes are instituted by the pilot in response to the GCA operator. The pilot's attention is not diverted in any manner. He knows each step is a precise 1° heading change and by maintaining the steering bar centered, bank angles are computed for him, enabling optimum correction to the new heading requirement.

The heading mode is used throughout the approach to the GCA recommended minimum altitude. The one variation in the GCA mode from the normal manual heading mode is a gain change which is initiated at GCA command "Begin Descent". A pilot-actuated mode select command enables a logic circuit at this point in the approach which increases the Bank/Heading ratio from a nominal 1.5/1° to 2.5/1°. Simultaneously the maximum bank command for any large heading error is limited to ± 15°. Thus, tighter control over the heading is assured as the approach window becomes smaller and faster correction to heading changes is realized.

The reference used to provide longitudinal steering is an airborn computed flight path angle. Refer to figure below.



θ -- Aircraft Pitch Attitude

α -- Angle of Attack

γ -- Flight Path Angle

The aircraft carries on board a prototype flight path angle computer. Provisions were made in the signal circuitry to enable the accurate selection ± 20° of flight path angle in ¼ degree increments. An error voltage about the selected angle was then available and displayed directly on the pitch steering bar. Thus the pilot could preselect any flight path angle he desired and be provided precise pitch steering information about that point. The basic requirements for lateral and longitudinal flight director steering have now been satisfied.

To follow the procedures used during a precision GCA, it is assumed a normal penetration has been accomplished and the intercept altitude has been established. It is noteworthy, however, that initial vectoring and let-down from cruise altitude could be accomplished with the heading and flight path angle flight director modes displayed and steering command information utilized throughout. Heading would be utilized in the normal manner (with the added convenience and precision of the remote heading set circuits) and the flight path angle selected to provide precise control of desired rates of descent.

After the glide slope intercept altitude has been reached, continued heading corrections would be responded to as required with the precision afforded by the remote heading set function. A constant altitude would be maintained

(Altitude Hold) and the flight path angle selector pre-set to the specific GCA glide slope angle and the longitudinal axis armed.

At the GCA operator's command to "Begin Descent", the pilot would depress momentarily the "Initial" button. This action automatically displays flight path angle error on the pitch steering bar, reflecting a positive error, providing a precise pitch-down command to establish a rate of descent consistent with the glide slope. Thus initial descent rates are established quickly and accurately.

A perfect track is seldom, if ever, maintained due to the many variables involved, i.e.: equipment accuracy, operator accuracy, and changing wind conditions. In the longitudinal axis the GCA operator's "high or low" calls may be responded to in several methods. The first could be a reselection of the flight path angle to establish a "closure" to the altitude commanded by the GCA operator. This can be accomplished by readjusting the flight path angle selector, or using the normal pitch trim button to change the selected flight path angle incrementally through small angles. When the "ON GLIDE Slope" call is received, the flight path angle could be returned (as above) to its original value; in the event of consistent "High or Low" calls, an increased or decreased flight path angle could be selected by the pilot as the case may be.

A second simpler method can be utilized alone or in conjunction with the first method. Closure to the proper altitude is simply established by flying the steering bar "off center" thus altering the actual flight path angle from that angle selected. If a "high" call was received from the GCA operator, the pilot would simply push forward and offset his steering command by some factor. Incidentally, a "high" call will result in a "high bar", and conversely, a "low" call results in a "low bar". When the "ON GLIDE PATH" call is received, the bar is returned to center and the selected flight path angle re-established. With very little practice a pilot becomes quite proficient in the amount of bar offset required for a given altitude error.

Progress of the approach is annunciated by the Landing Sequence Indicator since the approach and landing sequence circuits were armed with the command of "Initial". Thus the Middle Marker, 100 ft. and 50 ft. indications are displayed, as is the "flasher" at the altitude check points. At 50 ft. the selected FPA reference is removed and a one-step flare commanded, utilizing a preset .9° FPA reference. Touchdown disables the mode and rollout must be visual.

MODE SELECTION. Provisions for mode selection varied considerably; however, in most cases the pilot's control wheel became the prime area. Complete flight director mode switching and annunciation was assembled on "consoles" fabricated

for that purpose. Figure 29 illustrates how the control wheel consoles were mechanized and utilized to provide complete mode selection, approach sequence provisions and

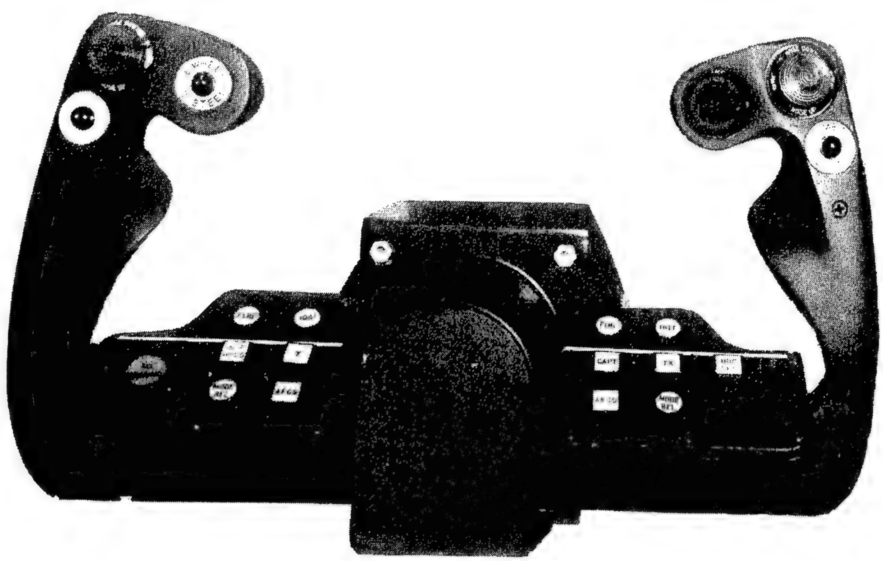


Fig. 29: T-39 Control Wheel

FDC/AFCS couple provisions. A two-level lighting system was employed, a low intensity level when not utilized and a higher intensity when a mode, sequence and/or coupled function was commanded. Dimming provisions which maintained the two-level lighting were also incorporated for pilot convenience. A sketch which graphically illustrates the wheel functions is shown in Figure 30.

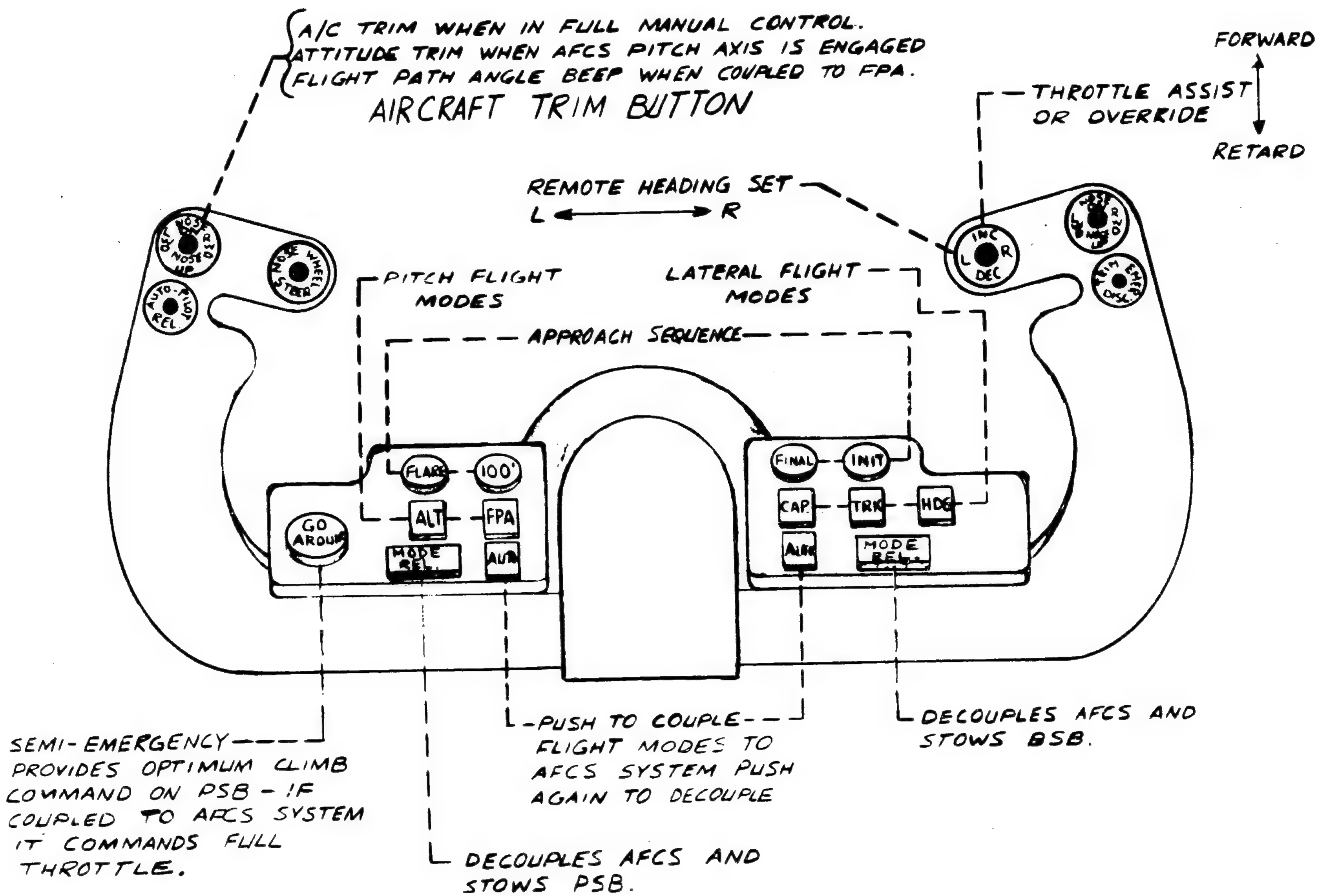


Fig. 30: T-39 Control Wheel

Other representative facilities for mode selection and annunciation on the control wheel consoles are illustrated in Figure 31. The "Bat Handle" in the rear of the left console is the GO-AROUND Switch and could be activated by the pilot, without removing his hand from the left grip. Otherwise, the left console was assigned to approach and landing sequence and the right console to the FDC/AFCS coupling switches. A requirement enabling AFCS coupling from either pilot or co-pilot side altered this configuration to that depicted in Figure 32. Push button logic supplanted the magnetic-held switches, and remotely located logic circuits enabled either pilot to "push on" for a couple or "push off" for uncouple using the same switch. The co-pilot's wheel is represented in Figure 33. This is the present wheel configuration of the T-39 aircraft engaged in the Weather Minimums investigation. The installation in this aircraft is unique in that the dual display groups were installed in the aircraft and operated from separate flight director computers, radar altimeters and other sensors. See Figure 34 for the overall Instrument Panel/Force Wheel configuration depicting the installation.

A single mode selector, located in the center of the instrument panel simultaneously affects mode selection of both FDC's. (See Figure 35). Also located in the center of the instrument panel is the AFCS/Auto throttle control panel illustrated in Figure 36.

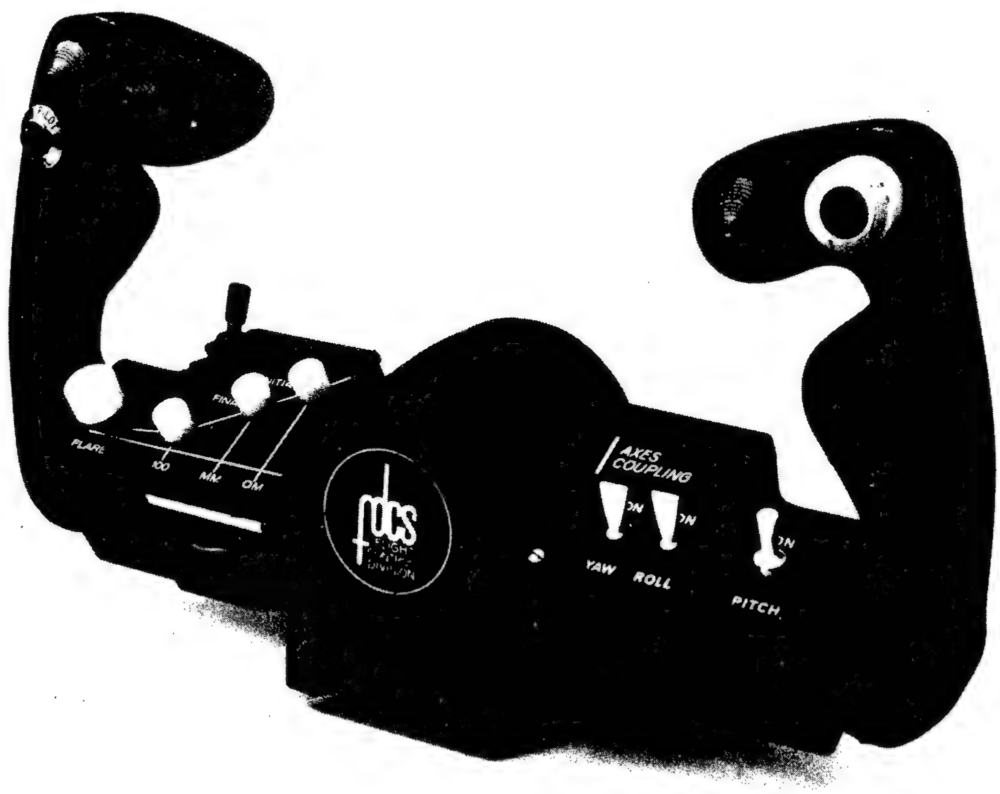


Fig. 31: T-39 Control Wheel

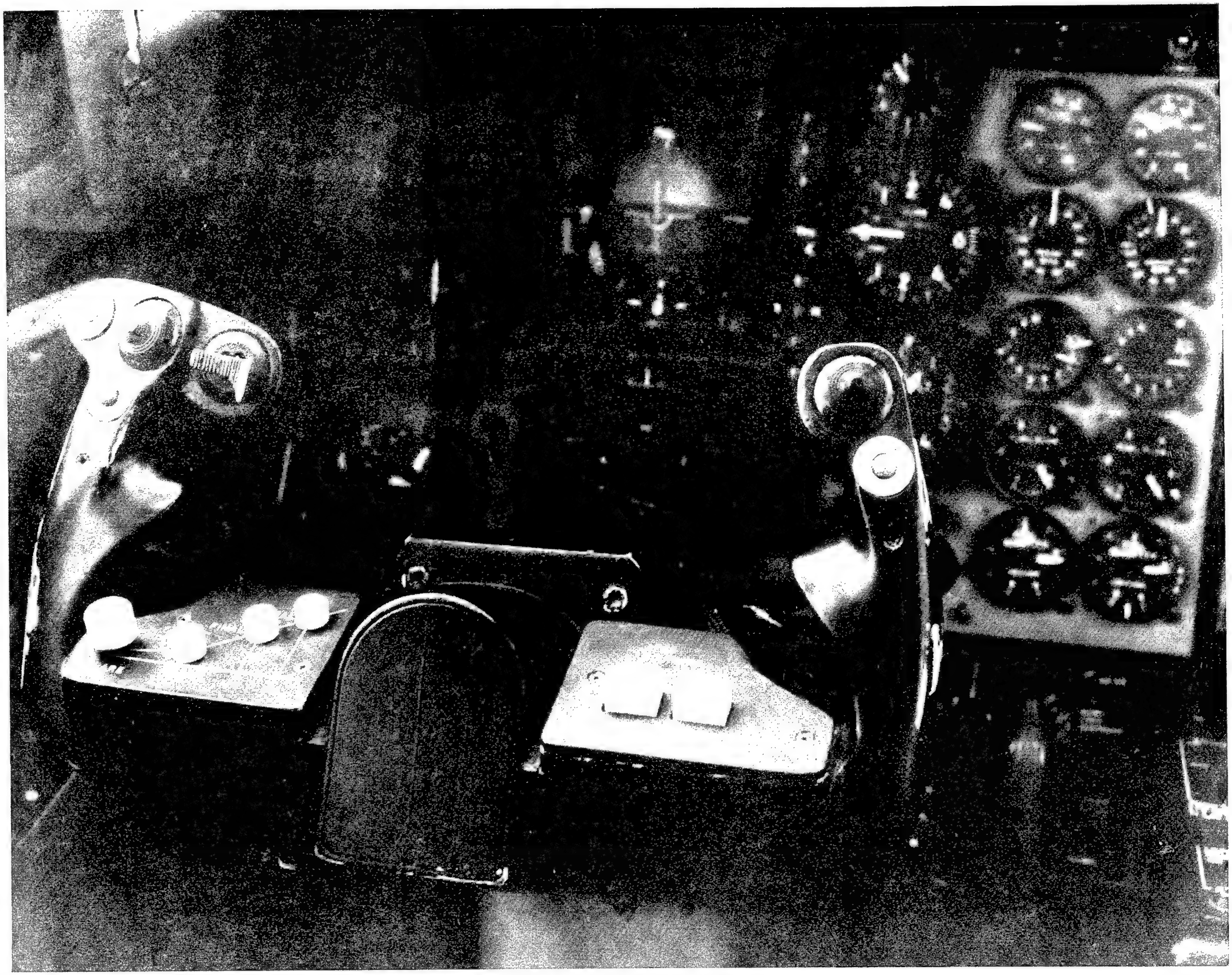


Fig. 32: T-39 Control Wheel (Pilot)

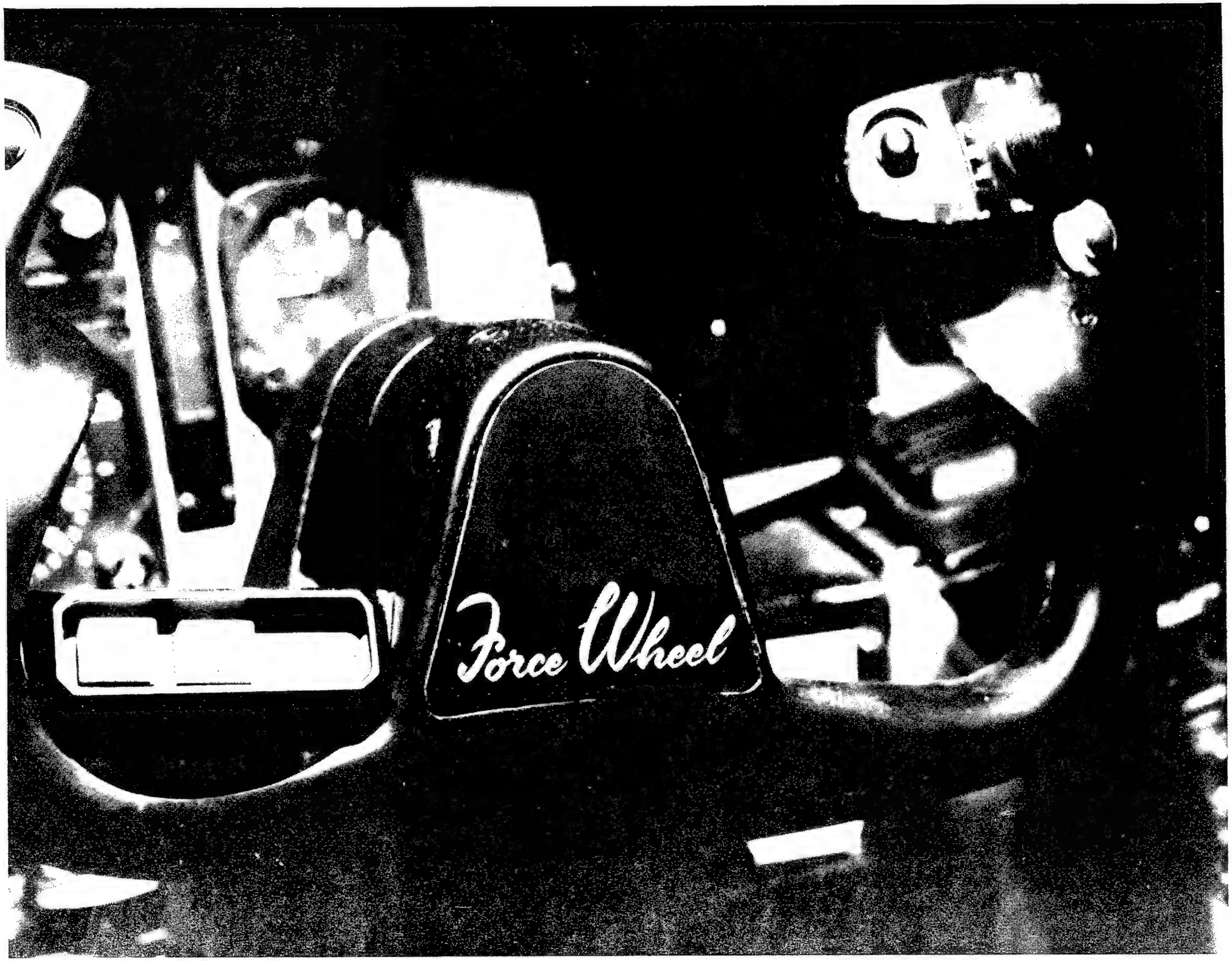


Fig. 33: T-39 Control Wheel (Co-pilot)

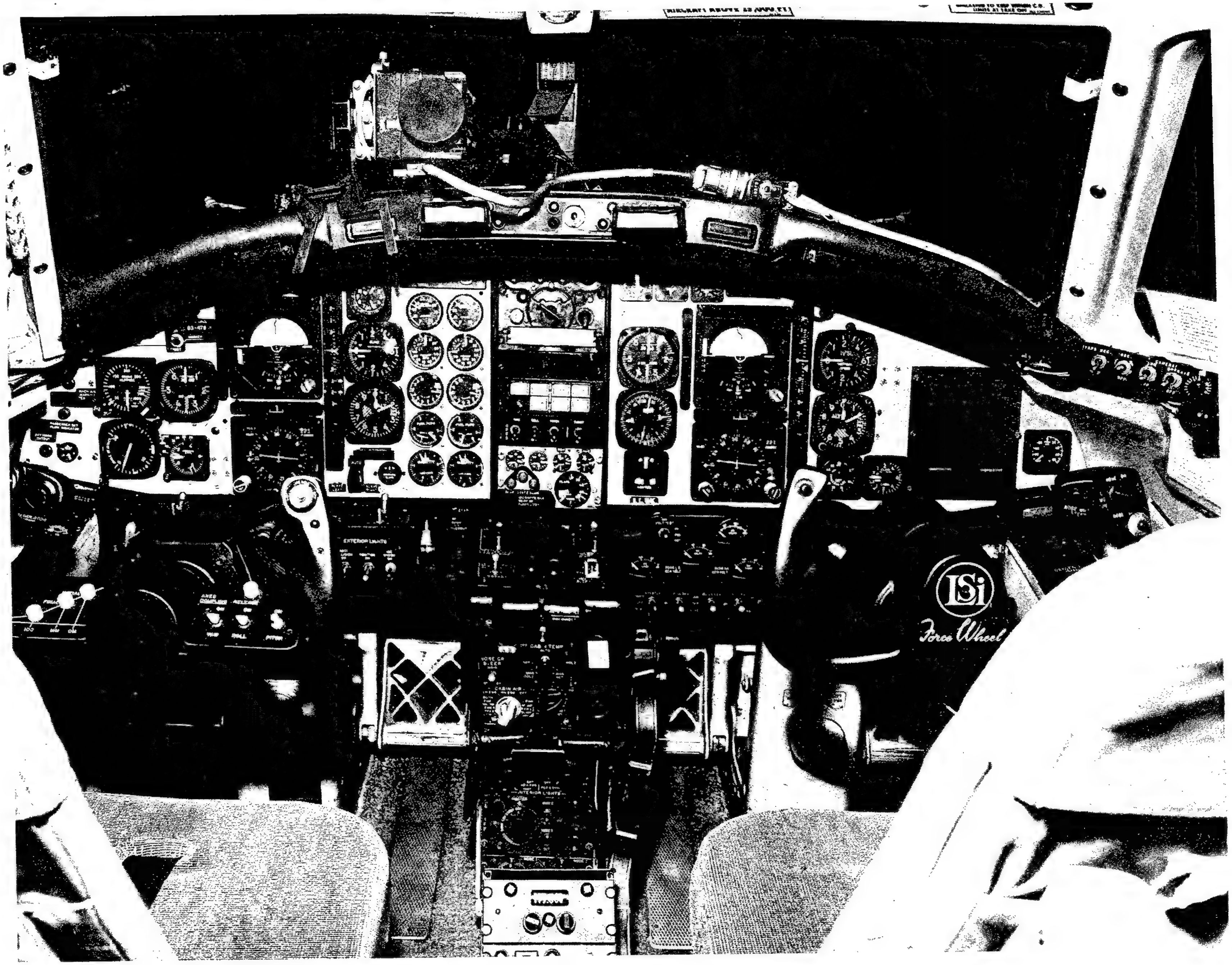


Fig. 34: Over all Instrument Panel Force Wheel Configuration

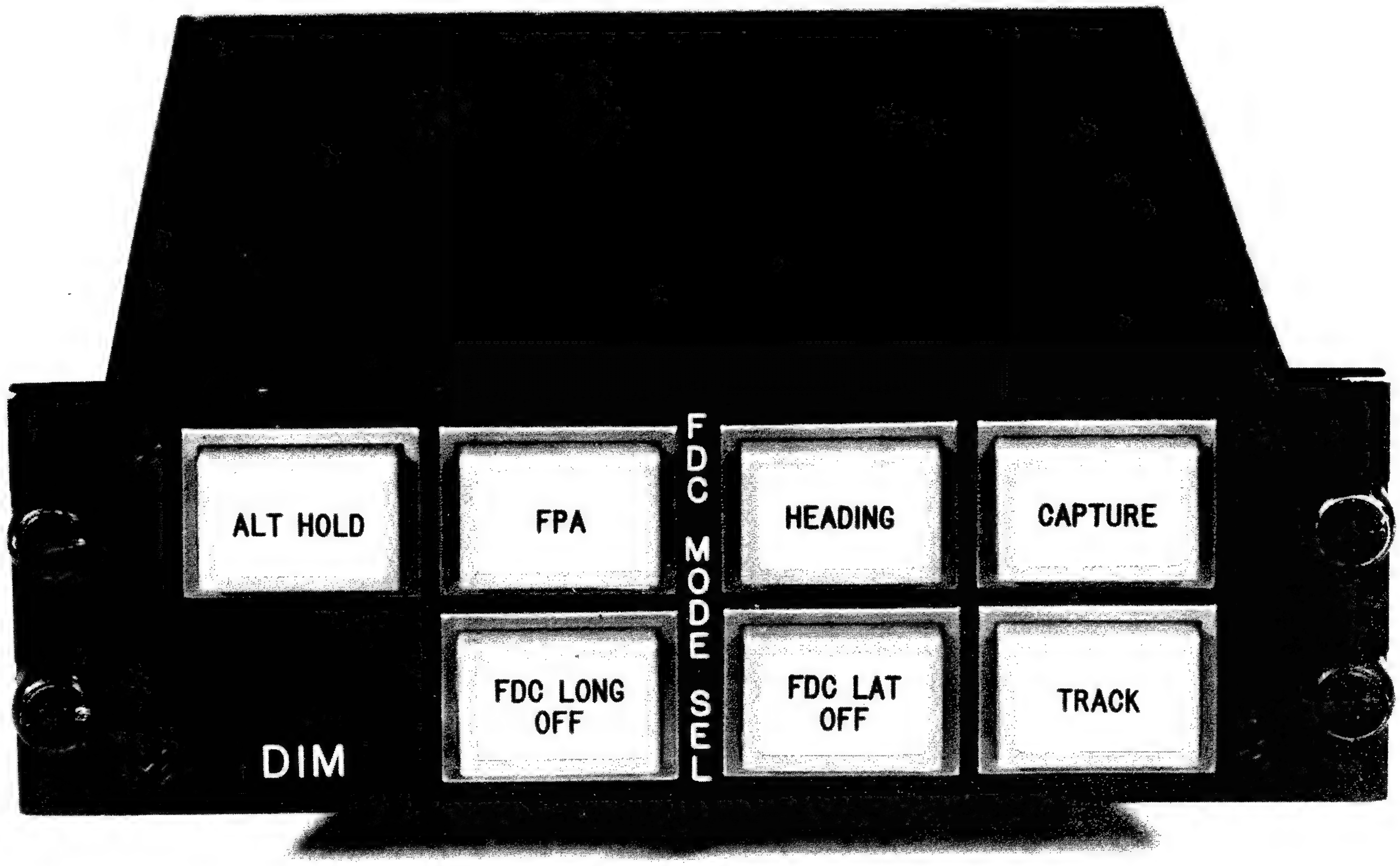


Fig. 35: FDC Mode Selector

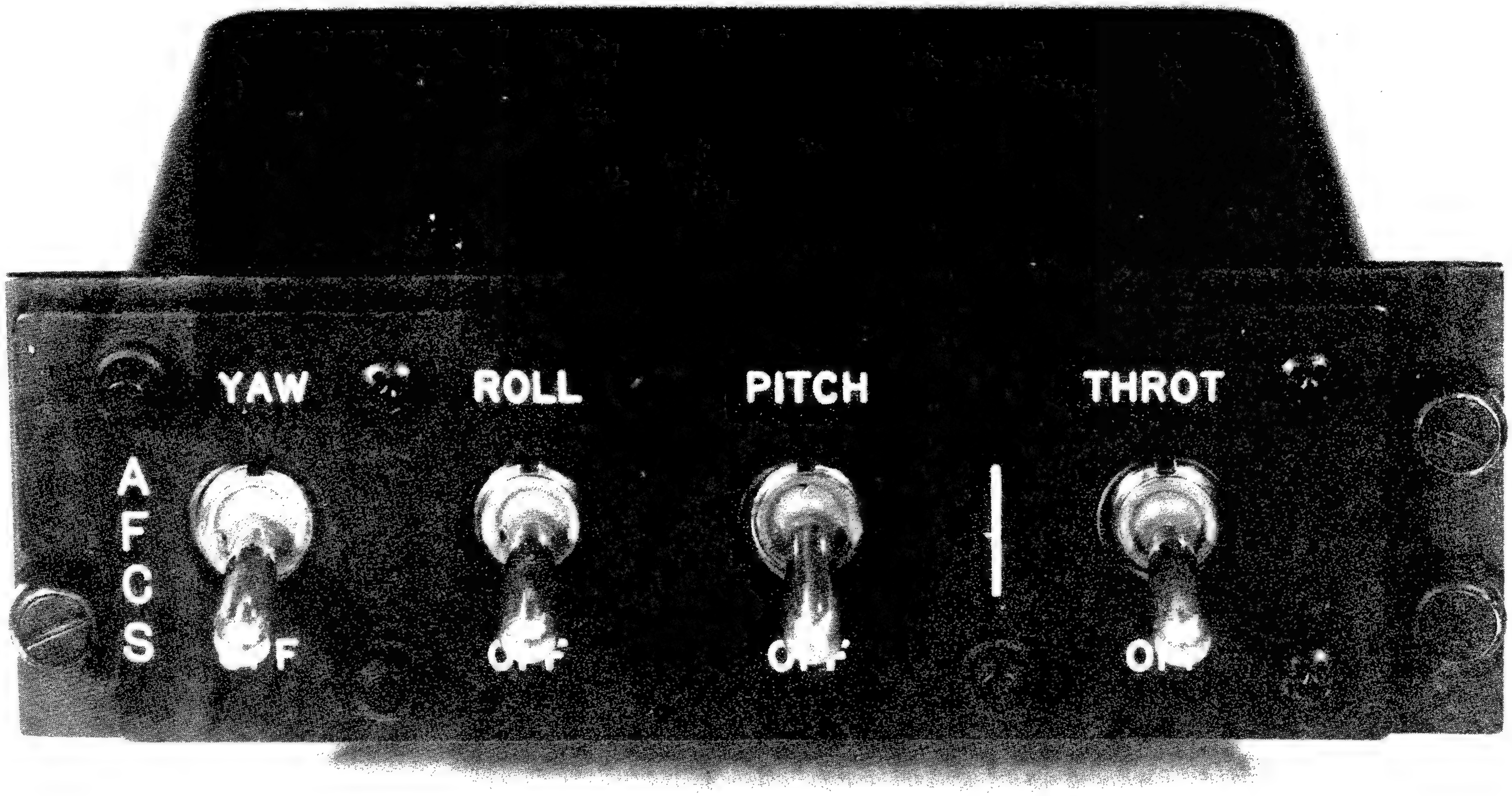


Fig. 36: AFCS/Auto Throttle Mode Selector

Additional controls were installed on a center "swing down" console, which in addition to providing more console space makes the control functions available to either pilot. In this installation, depicted by Figure 37, full selection of the navigation receivers and flight director computers is available to each pilot. A flight path angle selector, which provided a selected flight path angle reference to both FPA computers is also provided, as is the mode selector for the auto throttle.

The Automatic Flight Control System (AFCS) is an inherent part of the total system. The single three axis (yaw, roll and pitch) system was integrated with the flight director system and the capabilities presented by its installation were fully implemented. It is unique in many ways and utilizes the natural habits of the pilot thru force steering capability implemented in all axes. It is an excellent stable reference that can be altered thru normal pilot inputs at the control wheel and/or rudder pedals, and will maintain attitude reference and rate damping thru all pilot-induced manuevers.

Though initially supplied with a typical AFCS flight controller containing a turn knob and pitch command knob, the requirement for the flight controller was eliminated thru the implementation of the force sensors in the roll and pitch axes. In addition, and supplementing the force wheel steering

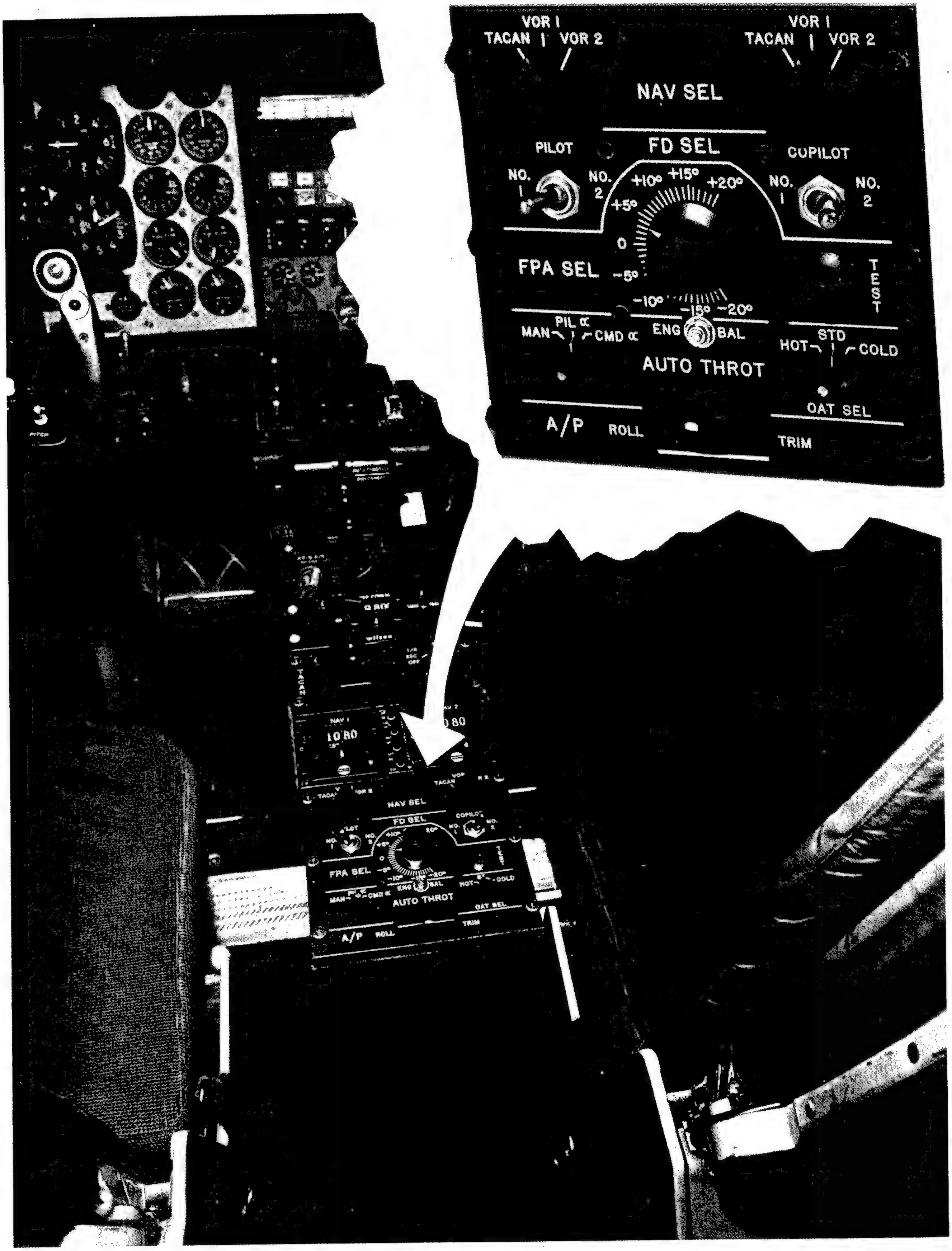


Fig. 37: Center Swing down Console Mode Selector

philosophy, several unique circuits were implemented.

Basically the three axes evolved are as follows:

YAW AXIS - in standard AFCS operation, this axis is essentially a damper system. However, in addition to the rate stabilization capability, pilot force command and turn coordination features were implemented. (See Figure 38). The latter assured aircraft turn coordination in the event a turn command was manually applied by the pilot at the ailerons and the required manual rudder inputs were not. Thus lateral split axis capability was assured.

ROLL AXIS - as mentioned earlier the requirement of the turn controller was eliminated thru the implementation of the force wheel. The pilot, by applying force, can readily command an over-ride of the basic wings level attitude reference of the roll axis to any bank angle he desires. The force required to accomplish this was mechanized as a simple force vs. attitude ratio and is an adjustable parameter. Removal of the force would result in the roll attitude loop returning the aircraft to a wings level attitude. To alleviate the requirement of having to maintain this force thru large bank angles and/or large heading changes during normal AFCS operation, additional circuitry was implemented in two aircraft. Termed "Roll Synchronization", the basic concept is outlined in Figure 39. Operationally, the pilot,

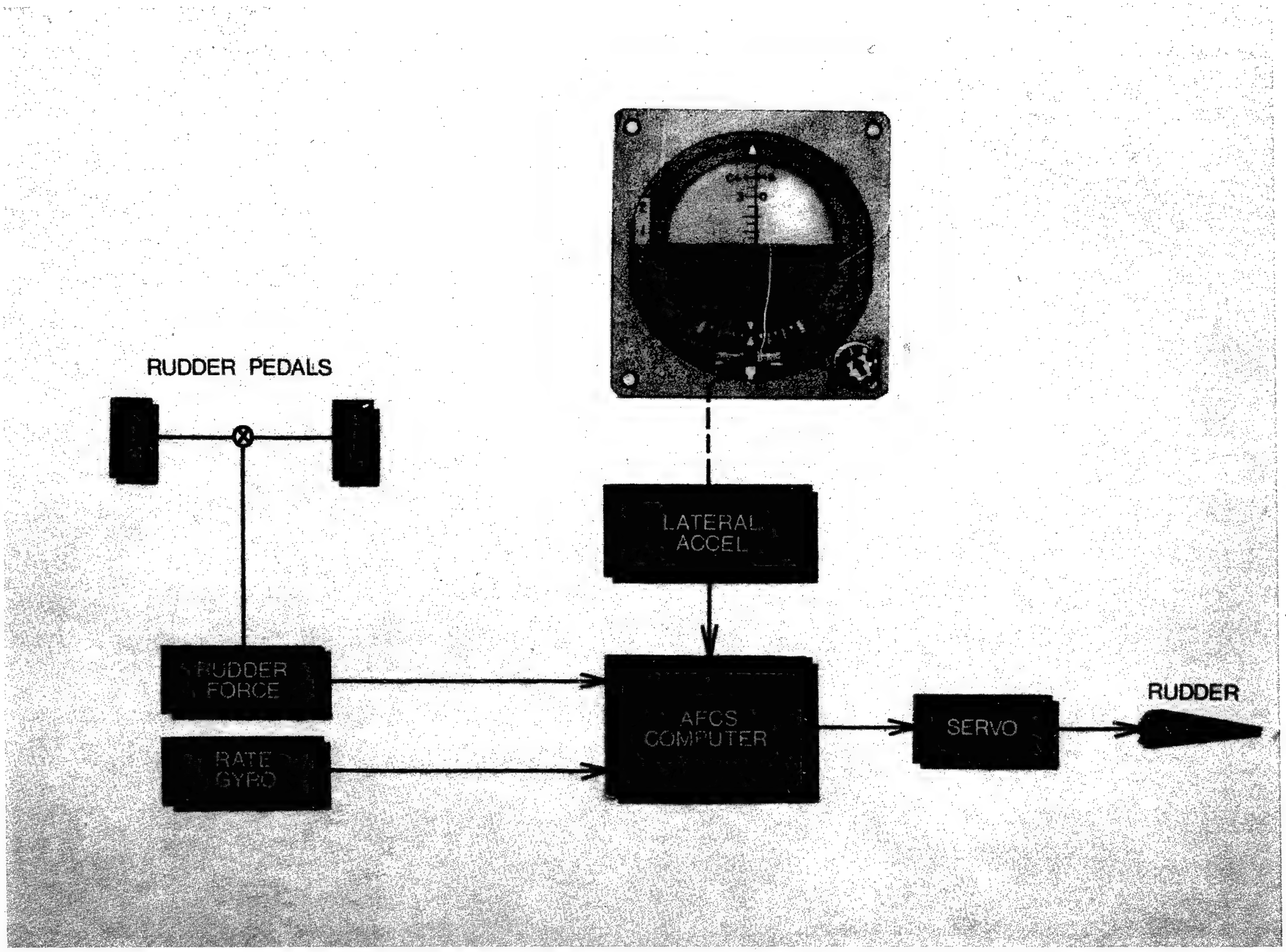


Fig. 38: Yaw Axis

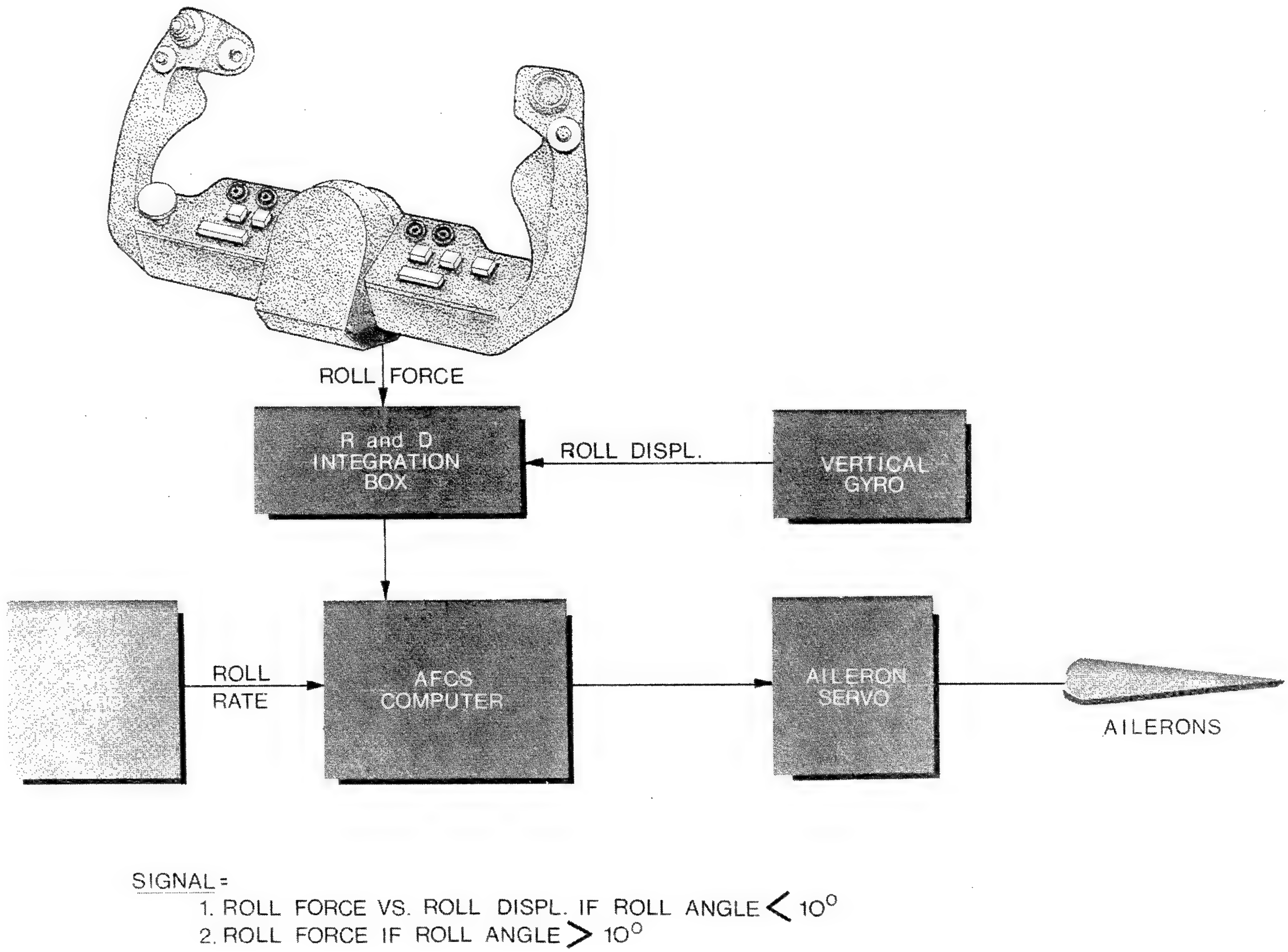


Fig. 39: Roll Synchronization

thru force applied at the normal control input, would command a change in basic aircraft roll attitude. For bank angles up to ± 10° the basic force/attitude ratio prevails and removal of the force input within the ± 10° range results in the aircraft returning to a wings level attitude. However, whenever the pilot would command a bank greater than 10° a completely different circumstance prevailed. As soon as the 10° angle is reached (or exceeded) the attitude is synchronized to the existing attitude. This immediately results in the force required to change the roll attitude to that approaching manual control. Thus what was a force vs. attitude ratio now becomes a force vs. rate ratio. Removal of force in this situation would result in the roll axis maintaining the bank angle which existed at the time, since the roll attitude reference was synchronized to this angle. Adjustment of one bank angle to another is accomplished by simply applying force until the desired bank angle is reached, then removing the force. As long as the desired bank angle exceeds 10°, that bank angle will be maintained. To return to wings level the pilot merely has to apply sufficient force to bring the aircraft to within 10° of bank. The final wings level adjustment is automatically accomplished by the normal roll axis circuitry. The roll synchronizer circuitry is enabled automatically upon roll axis engagement, remains operative during normal AFCS operation, but is rendered inoperative during all flight director coupled modes.

PITCH AXIS - this axis employs the standard pre-engage attitude synchronizer and incorporates an auto-trim feature. Both are standard AFCS features which insure that engage and disengage transients do not occur. Beyond this the project system differs radically. The pitch command knob on the flight controller was discarded due to the implementation of the force circuits employed, as illustrated in Figure 40.

Called "Pitch Force Fade", its implementation provided the pilot with complete control of the aircraft pitch attitude at the normal control input. Again the basic force vs. attitude ratio is established, whereas the AFCS pitch axis is commanded to a new attitude proportional to the force applied for short time intervals. Release of the force re-establishes the original pitch attitude prior to the application of force. If the pilot, thru normal force input at the wheel, commands an attitude change and maintains it, the force repositions the pitch command circuits over 2-7 second interval to the new attitude. As the pitch command circuits begin to drive toward the commanded attitude the force required to hold the attitude becomes less or begins to "fade" to zero as the attitude is approached. From this was coined the term "Force Fade". This feature is especially desirable when utilizing the AFCS during ascents or descents when relatively large pitch attitude changes may be required. For small attitude changes, circuitry is employed to utilize

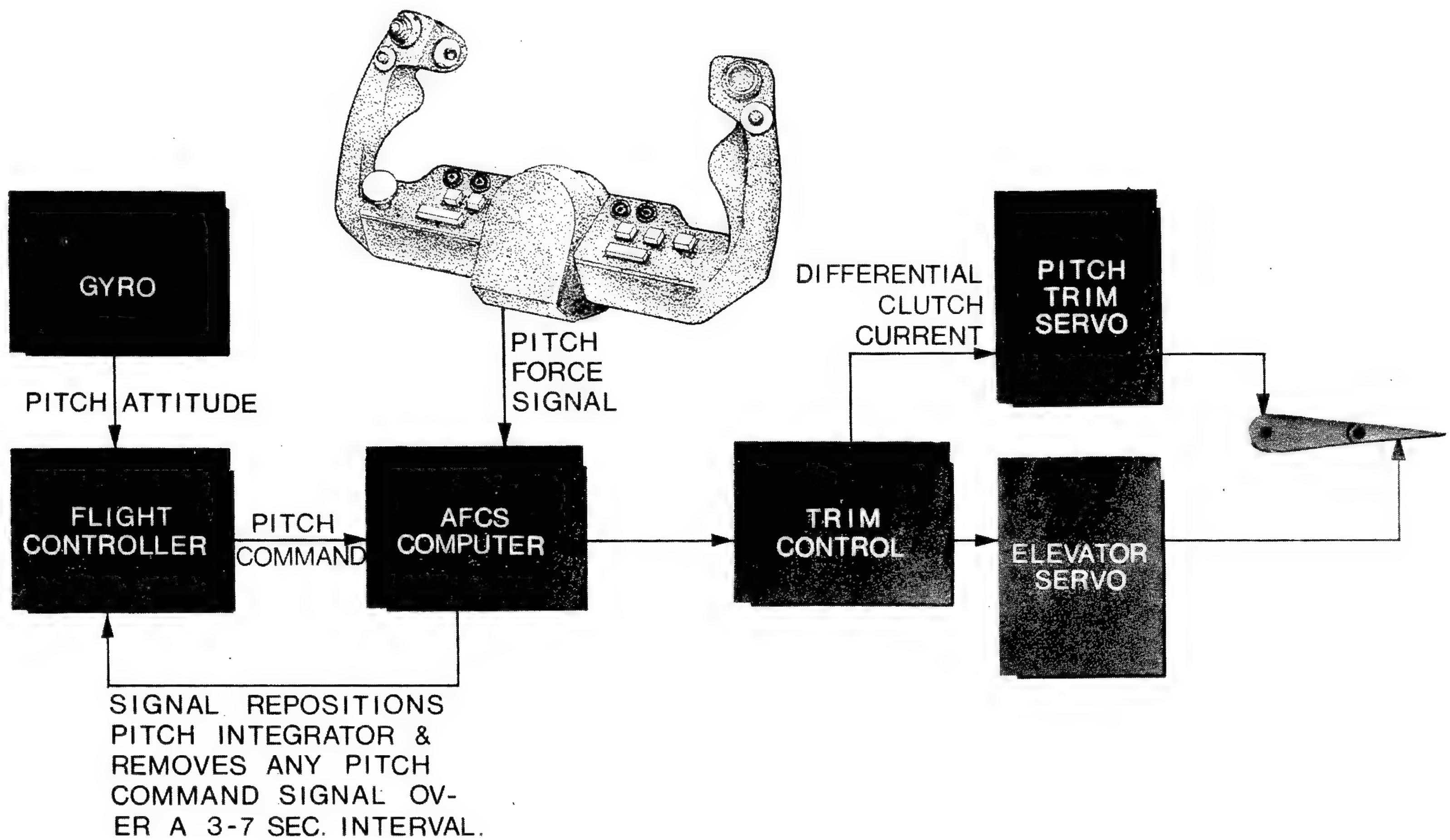


Fig. 40: Pitch Force Fade

the standard aircraft trim button. The force fade circuitry is again used; however, instead of being proportional to a force signal, a predetermined rate of attitude change vs. time of trim switch activation is employed. In this manner a "psuedo-incremental" attitude change is commanded by the pilot. Auto trim features of the AFCS insures a properly trimmed aircraft following any attitude change commanded by either method.

Each axis of the AFCS is independently selectable and any or all of the three axes may be engaged or disengaged at will. However, an AFCS release button is supplied at both the pilot's and co-pilot's control wheel. Activation of either button will disengage all AFCS axes simultaneously.

Versatility in AFCS axis engagement plus the added versatility of coupling only those AFCS axes desired to the flight director computer steering computations, provides the pilot with many options as to what control assistance he may select. Terms such as "Manual", "Semi-Automatic", and "Automatic" approach and landings were established to define this versatility and are explained as follows:

MANUAL - the AFCS is not engaged during manual operation. The pilot, though flying the flight director displays is employing manual control over the aircraft controls.

SEMI-AUTOMATIC - the AFCS is engaged; however, it is being utilized independent of the flight director system. The pilot has elected to maintain full command of the aircraft and is "in the loop" (through force control) commanding the AFCS in response to the visual flight director commands displayed.

AUTOMATIC - the AFCS axis/axes is engaged and being commanded by the information computed and displayed on the BSB and the PSB. The AFCS axis/axes is now defined as being "coupled" to the flight director signals.

There is also complete versatility in the total system. That is, any of the three AFCS axes could be in any of the three approach and landing modes described above. In addition, though not normal procedure, the AFCS axes may be engaged or disengaged, coupled or uncoupled without affecting the flight director mode selection or computation. This applies to any phase of the approach, landing rollout or rotate and go around. Flight director modes can be changed as required without affecting the AFCS couple function. Precautions were implemented to minimize control transients resulting from a sudden change in steering command which could result from the change in modes. Lastly, the release (mode off) of a flight director mode can revert any AFCS axis which is coupled to its basic function. eg: attitude hold in roll and pitch and damping in yaw.

Speed control computation is provided the pilot to improve approach and landing precision. The installation consists of an angle of attack display indicator graduated in units, and indexed to provide relevant information for flight parameters, and an apexer display on the glare shield. The signal input is derived from a left and right fuselage-mounted conical probe type transmitter. Utilizing this arrangement provides side slip compensation to the system. A block diagram of the speed indicator system is illustrated in Figure 41.

The indicator has graduations from zero to thirty units. Indexing provides a reference for the proper approach angle of attack for the aircraft, as well as the maximum range, maximum endurance and the approach to stall.

The apexer display, located on the glare shield, is a device consisting of three illuminated symbols - a chevron, a circle or donut, and an inverted chevron. The circle denotes an on-speed condition for approach. The chevron indicates to the pilot he is slow and the inverted chevron indicates he is fast. The apexer also contains a pointer which reflects the same movement as the pointer on the panel indicator but over a more narrow range about the approach reference speed.

Utilizing the recommended aircraft angle of attack for speed control during approach and landings insures that the correct

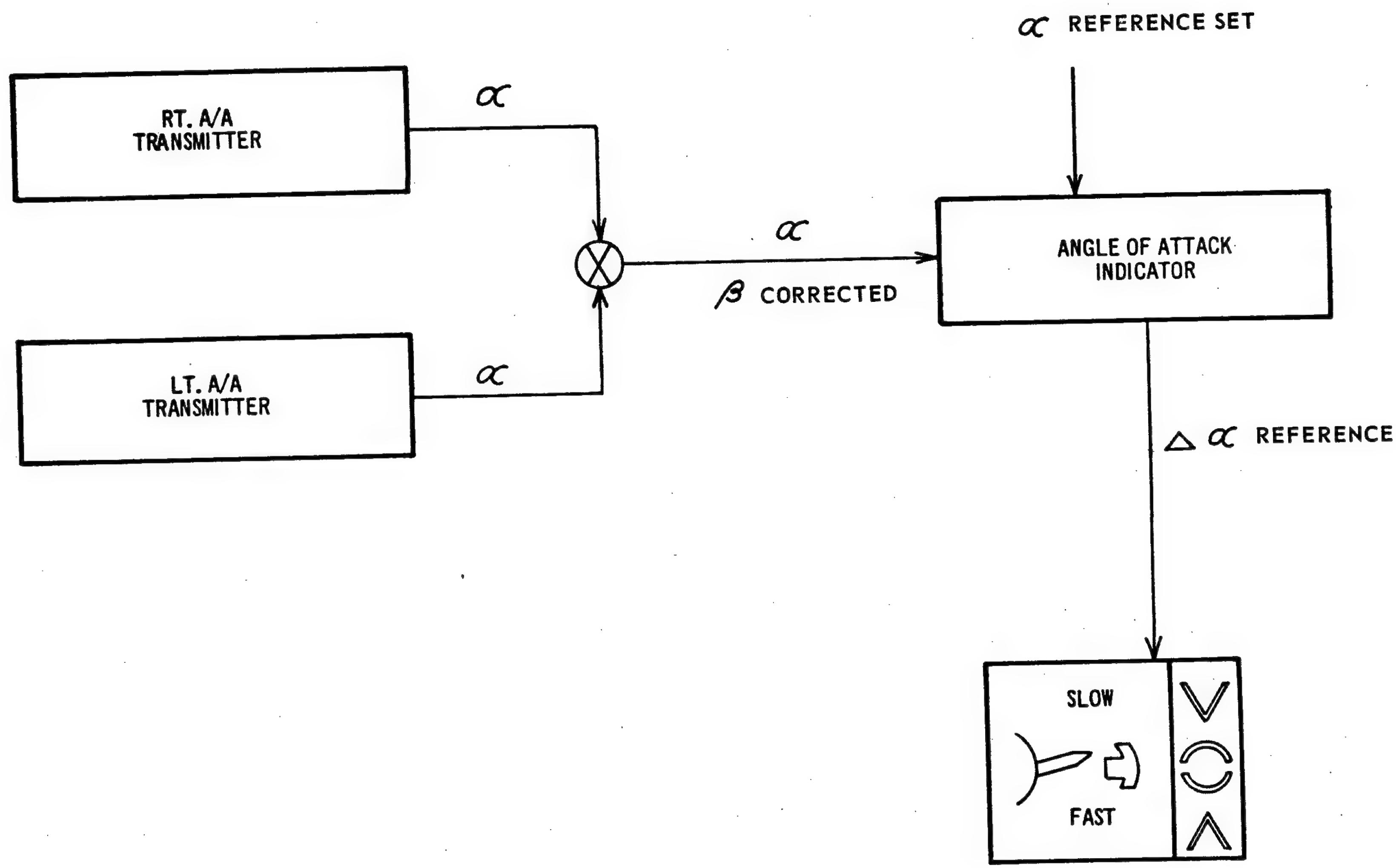


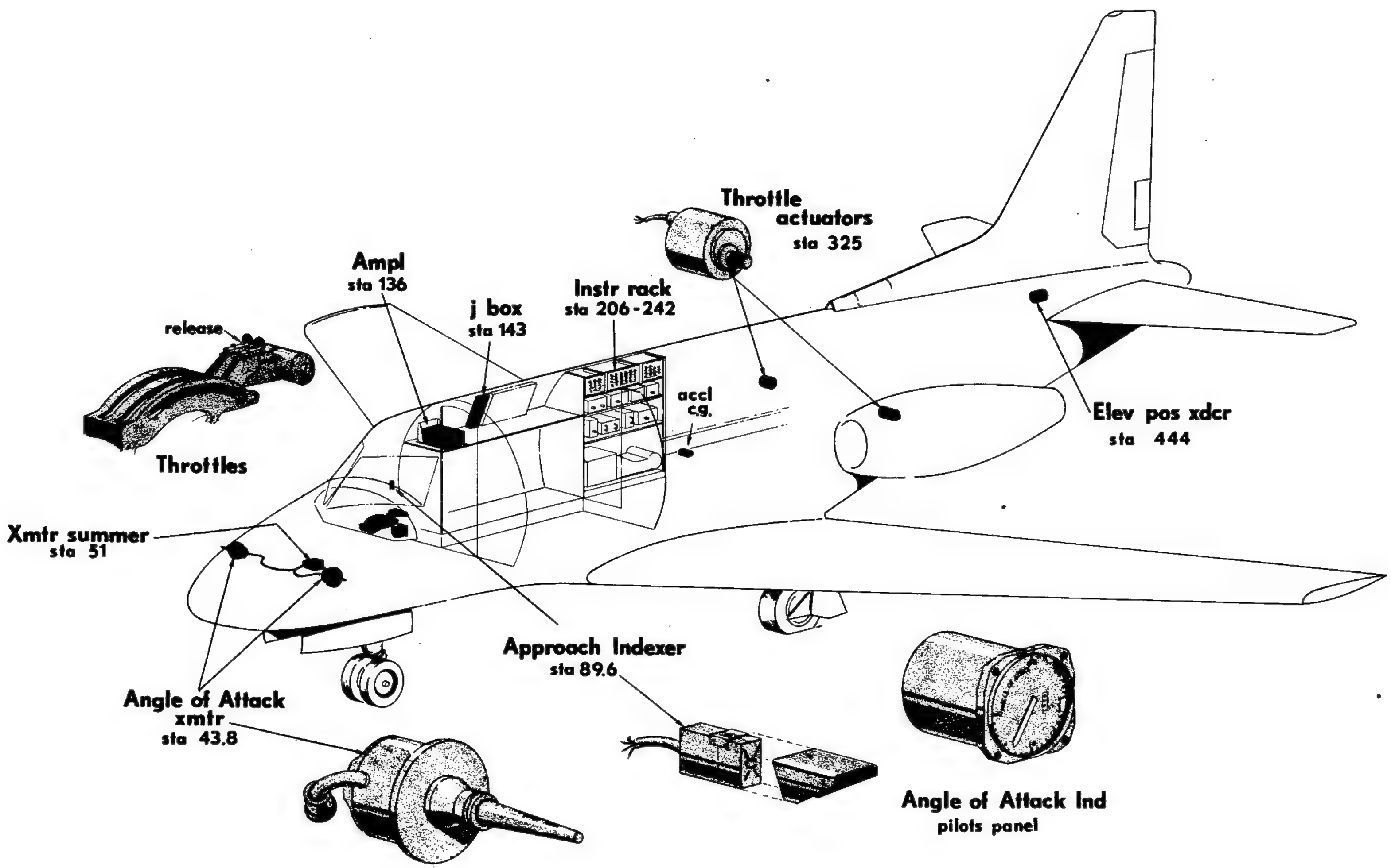
Fig. 41: Block Diagram of Speed Control System

approach air speed is maintained irrespective of attitude changes, turbulence and gross weight, without the need for "dial" or "bug" settings by the pilot.

To round out the total automaticity of the system, the angle of attack sensors utilized as the signal source for the display system were also utilized to provide the essential control parameter for an Automatic Throttle system installation. Figure 42 illustrates the total installation.

The Automatic Throttle System (ATS) consists of a computer, two amplifiers, interface network, and two servo actuators. The input to the system consists of signals summed from left and right angle of attack transmitters, a normal accelerometer, and an elevator position transmitter. The summed and averaged angle of attack input, providing side slip compensation, is the primary control function. The normal accelerometer provides damping for wind shear, gusts and other disturbances. The elevator position signal provides angle of attack change anticipation. See Figure 43 for an overall functional diagram.

Additional discrete information, for correct processing of the continuous signal inputs, is provided by the system engage switch, ambient temperature switch and interlock switches such as landing gear strut compression switches. One other input is utilized. This is a discrete 50-foot



APPROACH POWER COMPENSATOR EQUIPMENT INSTALLATION | a flight control division project

Fig. 42: Auto Throttle System Installation

point obtained from the radar altimeter. This functions to change the angle of attack reference and operate the throttles to provide proper power for landing flare. At touchdown (strut compression) the system disengages. The pilot also has several options for disengage and overpower of the system.

The computed thrust command signal is based upon maintaining a safe margin above stall during the approach, i.e., FAA approach criteria of 30% or 1.3 V_s. The automatic throttle system provides this safety margin by maintaining a dynamic angle of attack which is referenced in the computer to the angle of attack corresponding to the appropriate approach criteria. Deviation from the reference will cause the automatic throttle system to call for and provide an increase or a decrease in thrust as required to hold the aircraft "on speed" or on reference. Movement of the elevator provides a signal calling for increase or decrease thrust so that attitude changes do not upset the reference speed. During approach, utilizing the automatic throttle system, the indicator and indexer provide performance monitoring.

One additional area remains to be described and pertains to the "Heads Up" display concept. The display, called a Peripheral Command Indicator (PCI), is installed as a heads up flight command indicator which enables a simple transition

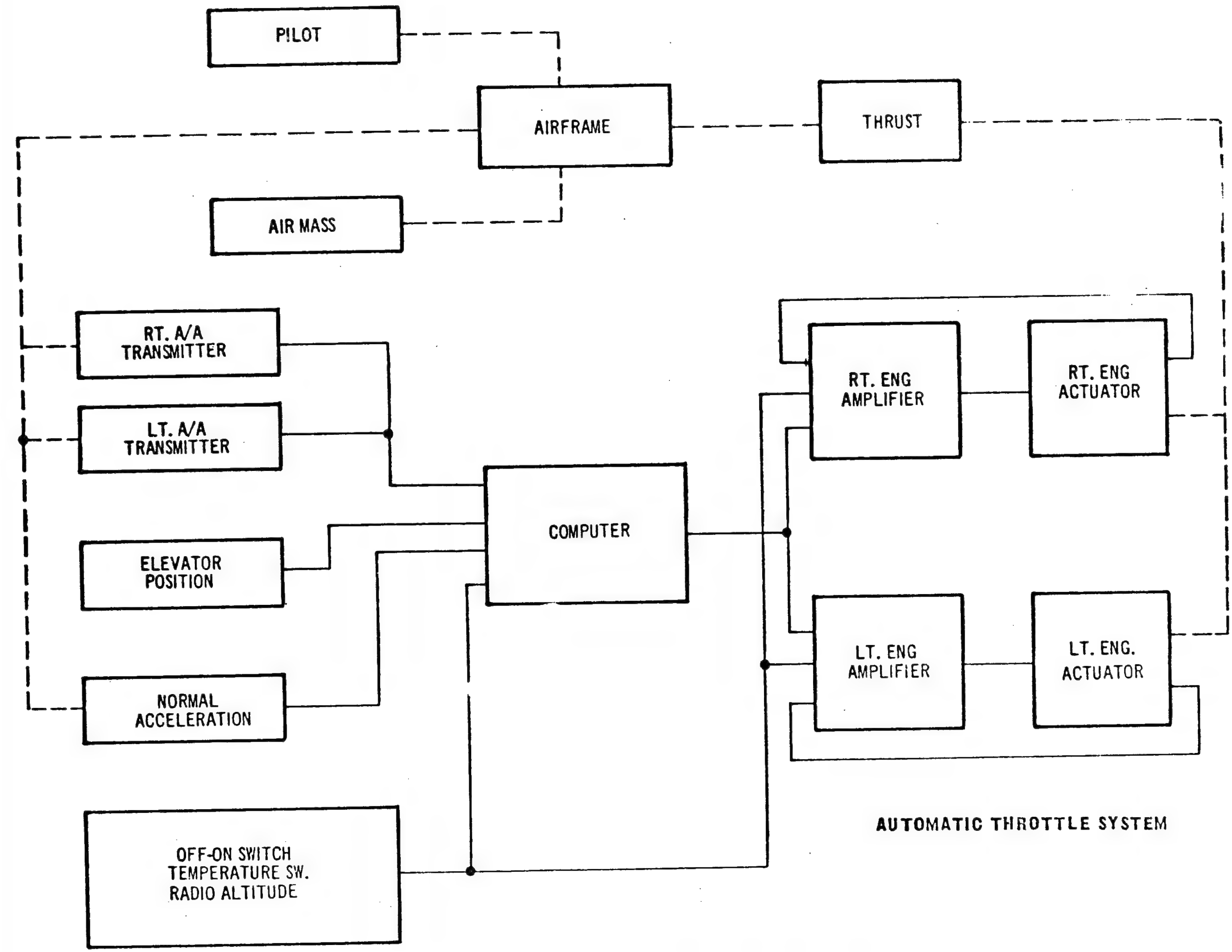


Fig. 43: ATS Overall Functional Diagram

from IFR to VFR reference during all weather landings. Several generations of these displays have been installed; however, the latest device is illustrated in Figure 44.

The indicator displays roll and pitch commands, speed command, absolute altitude and raw localizer deviation.

The roll and pitch commands are represented by a diamond-patterned rate field. The rate of movement (adjustable) is proportional to the steering command. For a true roll command the diamonds appear to rotate. The pilot would bank the aircraft in the direction of movement. When the proper bank angle is reached the movement stops. For a pitch command the diamonds appear to move vertically. The pilot would pitch the aircraft in the direction of the diamond movement. The pitch command is satisfied when the diamonds stop. The diamonds are servoed as a direct function of flight director lateral and longitudinal computations.

Speed command is represented by a series of lights moving vertically in the center of the unit during CAPTURE and TRACK modes. When these lights move up, it is commanding forward throttle and more thrust. Conversely, when the lights move down, it is commanding a throttle retard and less thrust. The referenced thrust command is based upon angle of attack and takes into account aircraft gross weight and flap position. The signal is a duplicate of the signal displayed on the slow-

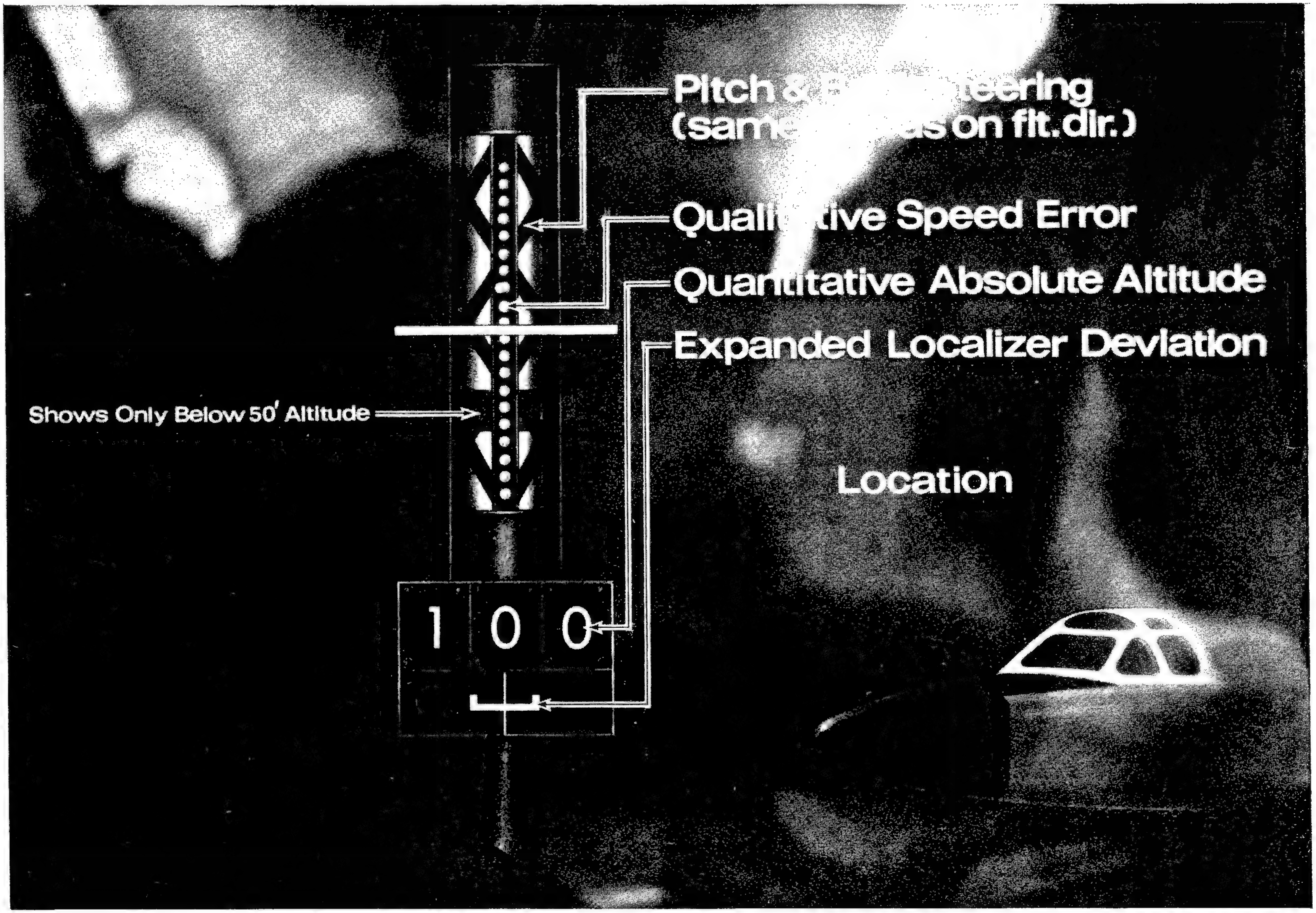


Fig. 44: Peripheral Command Indicator

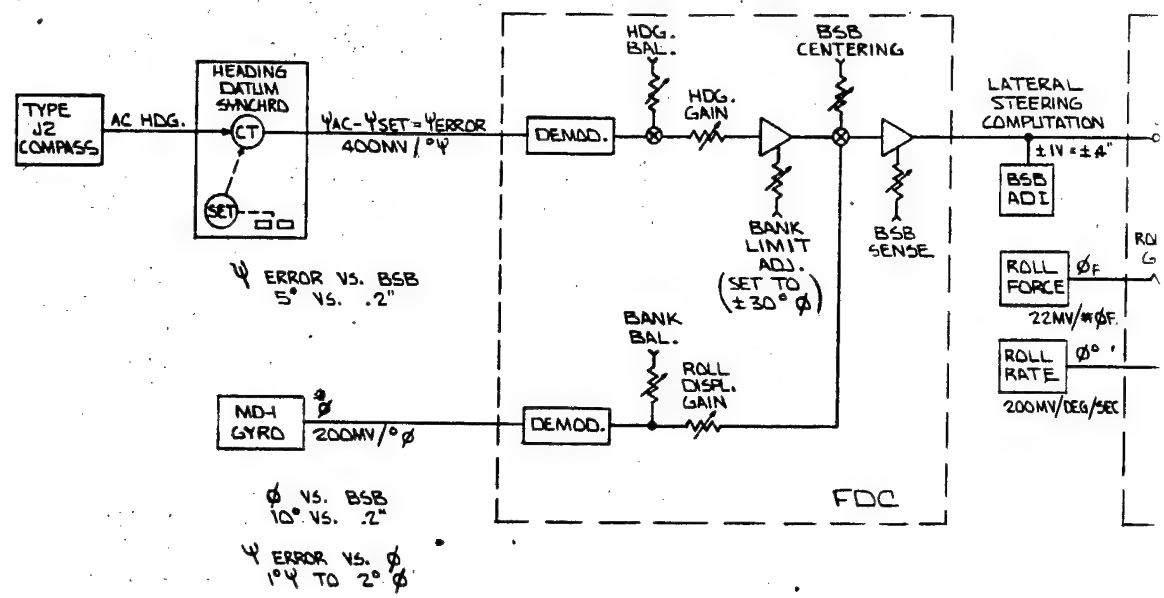
fast indicator to the left of the ADI on the instrument panel. An "on speed" condition will have an equal number of lights above and below the unit's center line denoted by the cross bar. Presently a total of four lights are used.

Absolute altitude is indicated in two ways. The first (and original) method represents altitude as a green flag which appears at the bottom of the rotating diamond window, at 50 feet, and moves up toward the center of the PCI as altitude decreases. As the leading edge of the flag reaches the center of the PCI, it is indicative of touch-down. The second method is a numerical readout and is still in proto-type stage. Discrete altitudes, still to be selected through flight test, will be displayed in digital form. The purpose of the readout is (in-part) to provide a definite indication of approach progression thru the decreasing altitude read-outs. In addition, during the terminal portion of the approach (150 ft. to touch-down) the altitude between readouts will be reduced to see if rate of closure information will be presented by the changing readouts. Presently the unit is planned to display altitude in 5 ft. increments from 50 ft. to touchdown. The signal to drive the altitude displays are referenced to the radar altimeter which provides an accurate and precise absolute altitude signal.

On the bottom of the PCI there is a meter movement symbo-lizing the runway. The raw localizer signal is processed to

expand the scale gradients and to operate the meter movement which displays precise localizer position. Operating within the vertical tips of this meter movement will provide safe landings within the confines of the runway. This meter is a duplication of the expanded localizer indication as used in the lateral situation indicator.

This completes the description of the basic systems and displays utilized in the synthesis and investigations of conceptual areas of the approach and landing phases.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AC HDG.
HEADING DATUM SYNCHRO
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SET
ΨAC-ΨSET = ΨERROR
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DEMOD.
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HDG. GAIN
BANK LIMIT ADJ. (SET TO ±30° φ)
BSB CENTERING
BSB SENSE
LATERAL STEERING COMPUTATION
±1V = ±.4"
BSB ADI
ROLL FORCE
φF
22MV/°φF
ROLL RATE
200MV/DEG/SEC
Ψ ERROR VS. BSB
5° VS. .2"
BANK BAL.
ROLL DISPL. GAIN
MD-1 GYRO
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Ψ ERROR VS. φ
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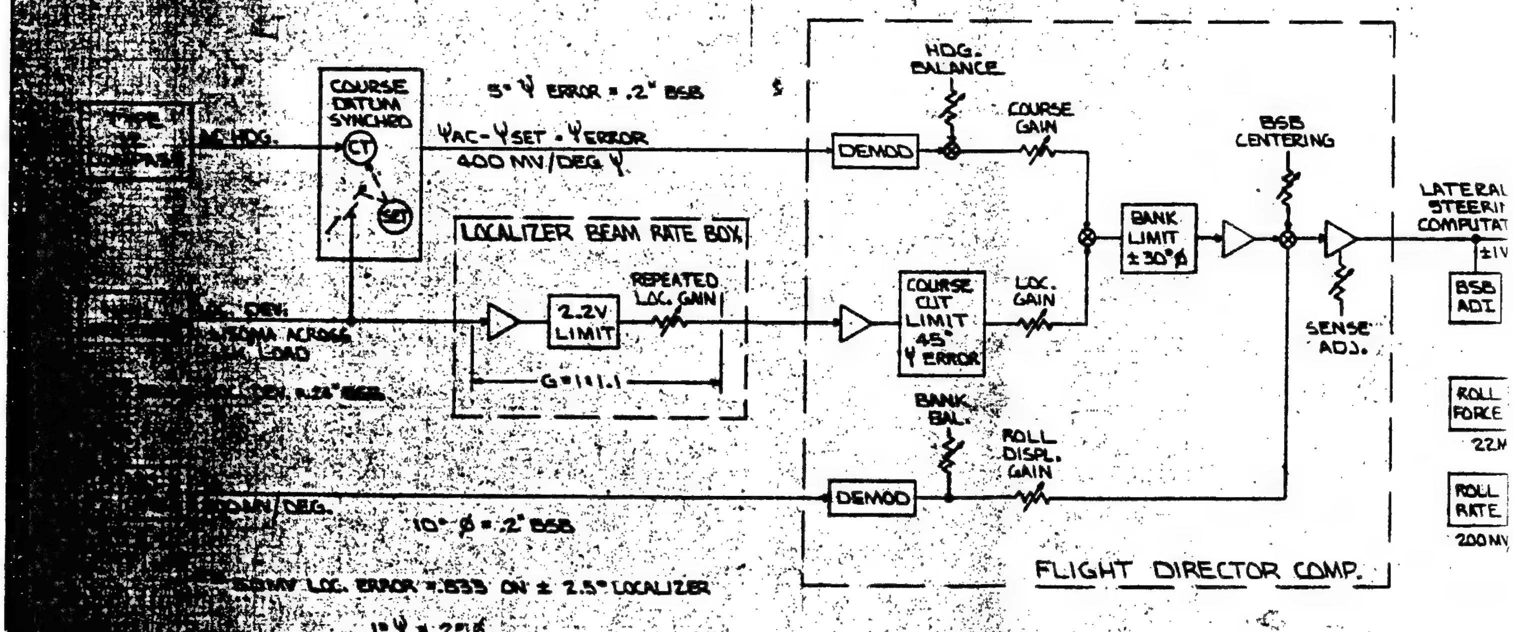
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AC HDG.
5° Ψ ERROR = .2" BSB
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COURSE GAIN
DEMOD
LOCALIZER BEAM RATE BOX
2.2V LIMIT
REPEATED LOC. GAIN
G=1:1.1
COURSE CUT LIMIT 45° Ψ ERROR
LOC. GAIN
BANK LIMIT ±30°φ
BSB CENTERING
SENSE ADJ.
LATERAL STEERI
COMPUTAT
±1V
BSB ADI
ROLL FORCE
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BANK BAL.
ROLL DISPL. GAIN
DEMOD
10° φ = .2" BSB
FLIGHT DIRECTOR COMP.
1°Ψ = 2°φ

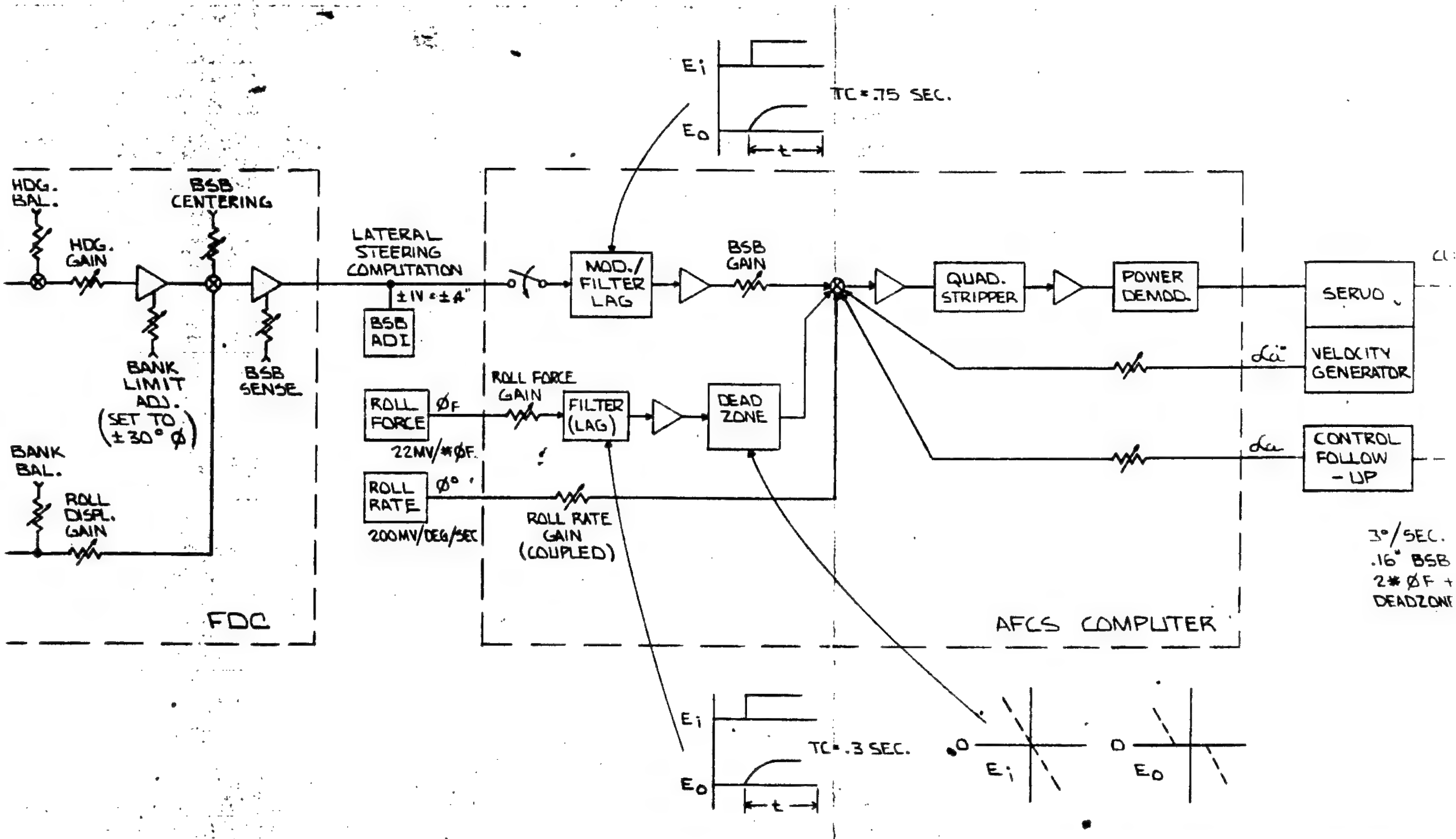

Fig. 45: Heading Mode Signal Flow and Computation

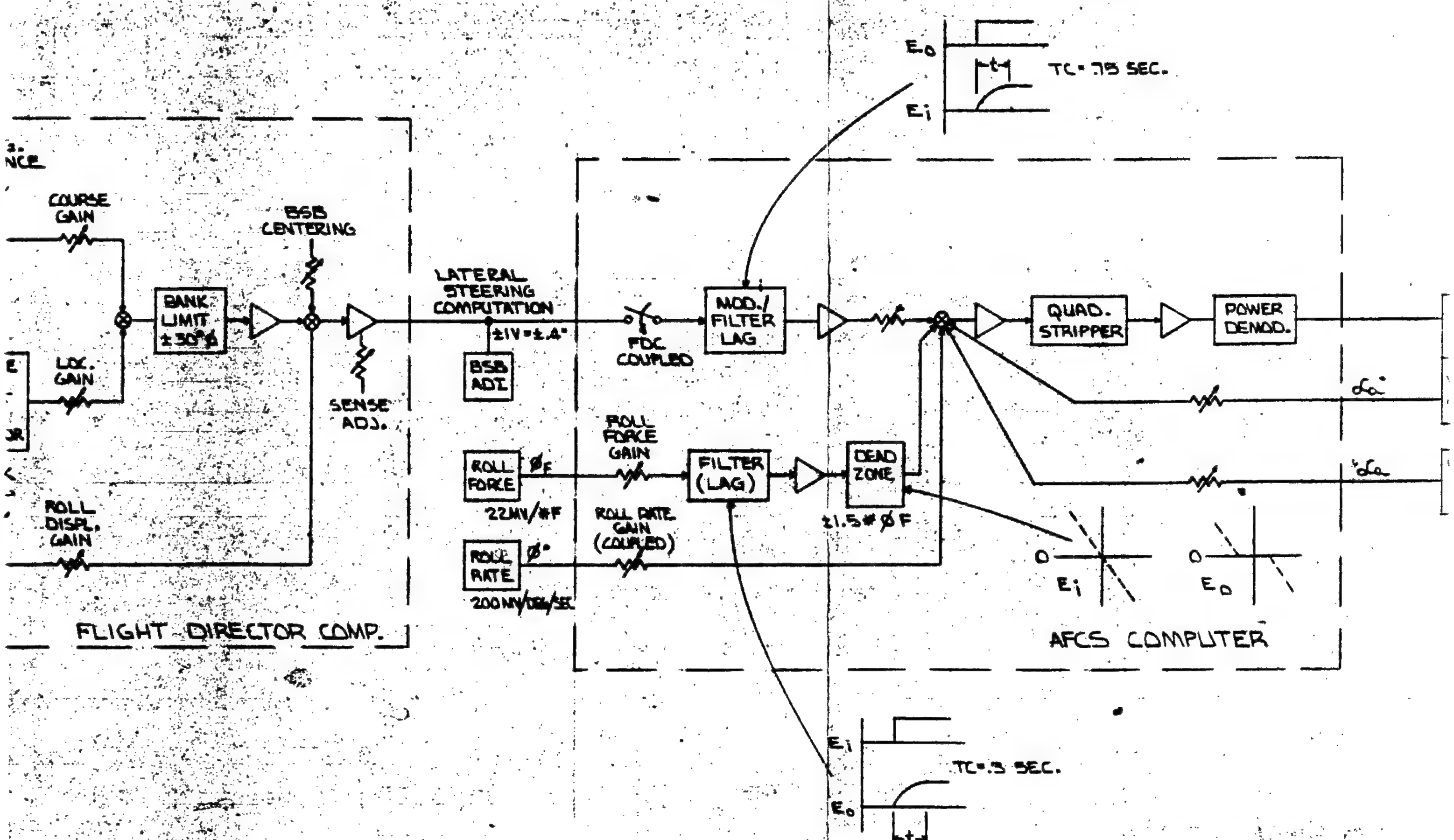

Fig. 46: ILS Capture Mode Signal Flow and Comput

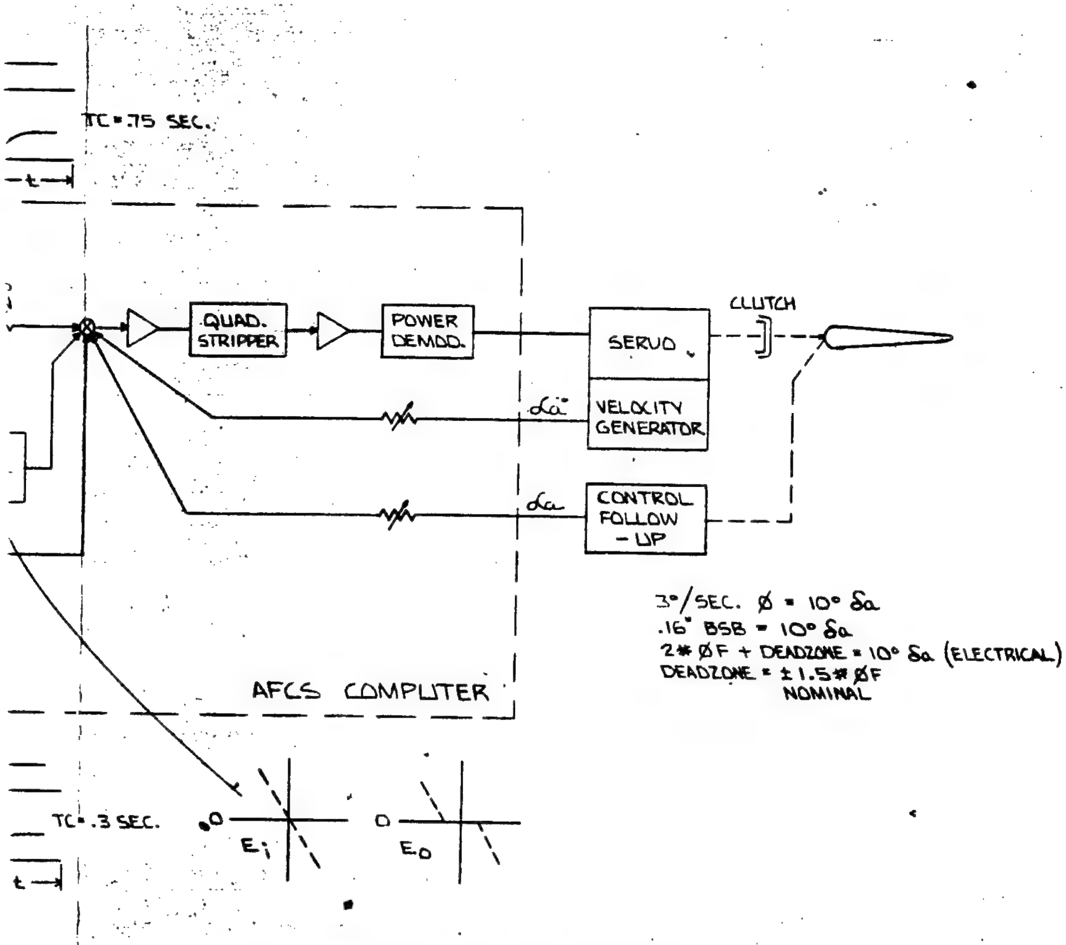

Fig. 45: Heading Mode Signal Flow and Computation

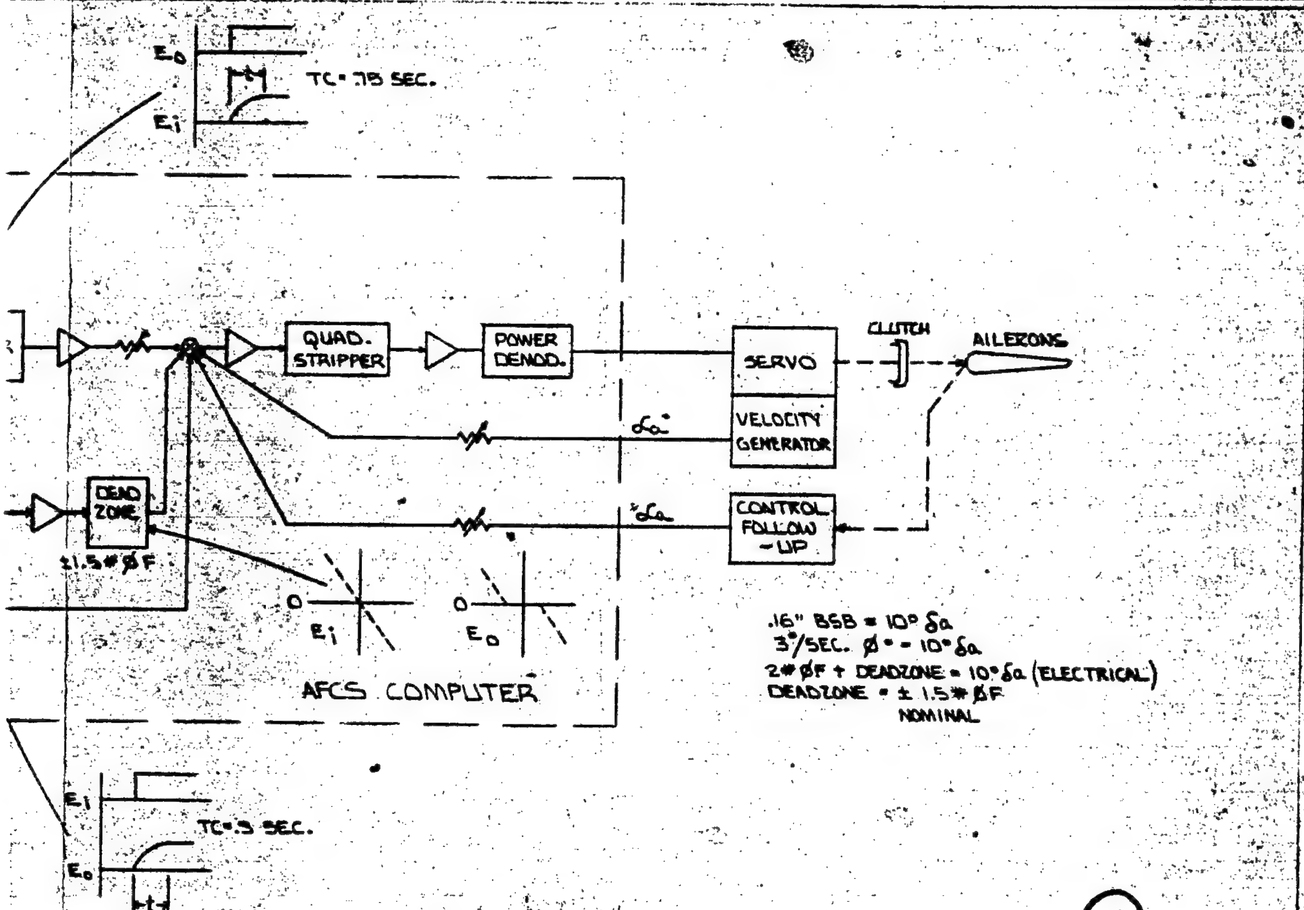

Fig. 46: ILS Capture Mode Signal Flow and Computation

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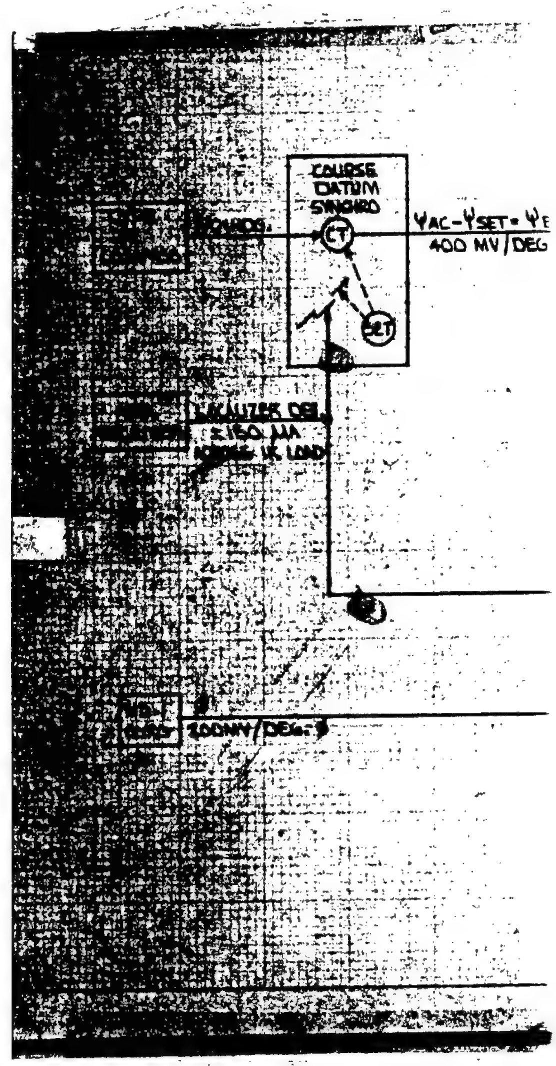
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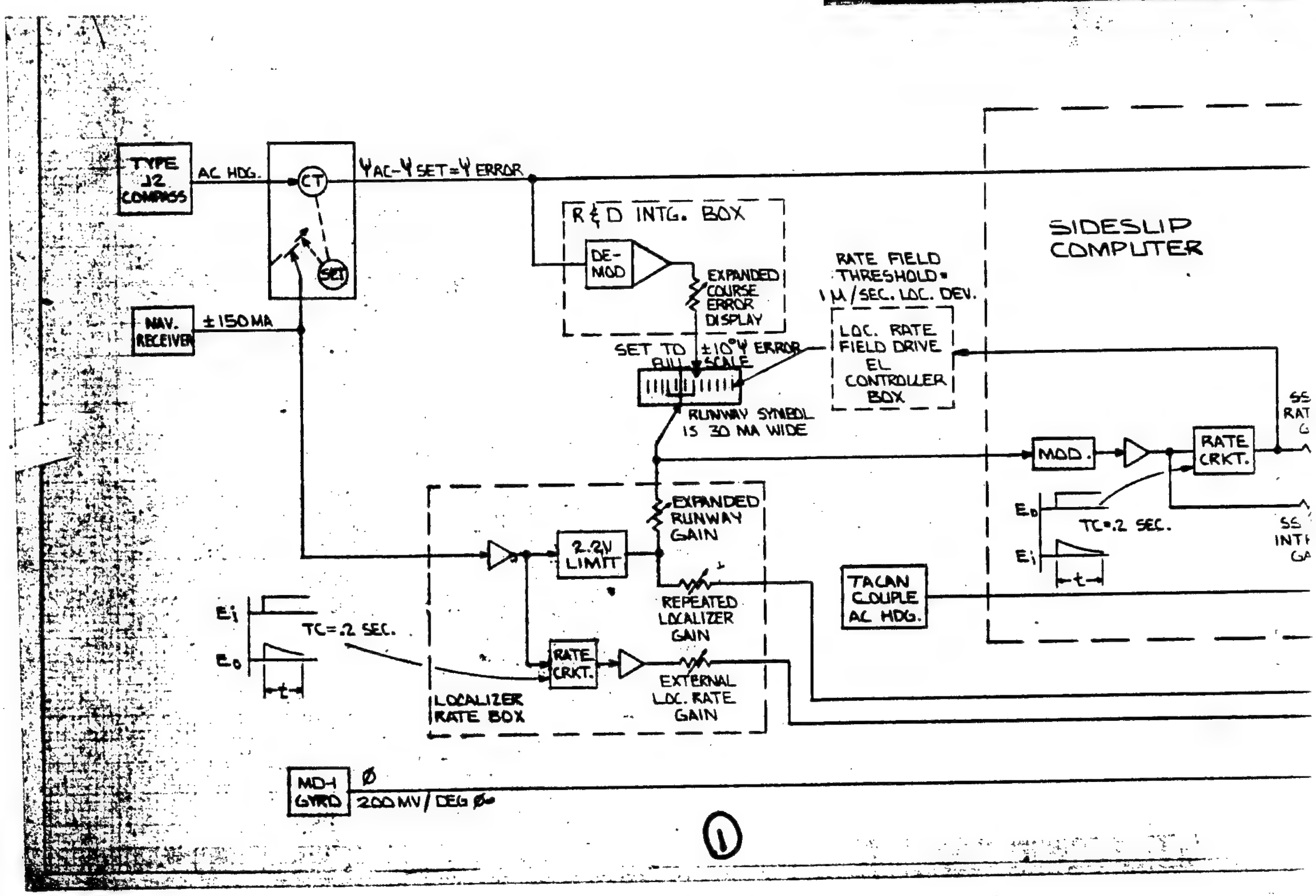
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CT
SET
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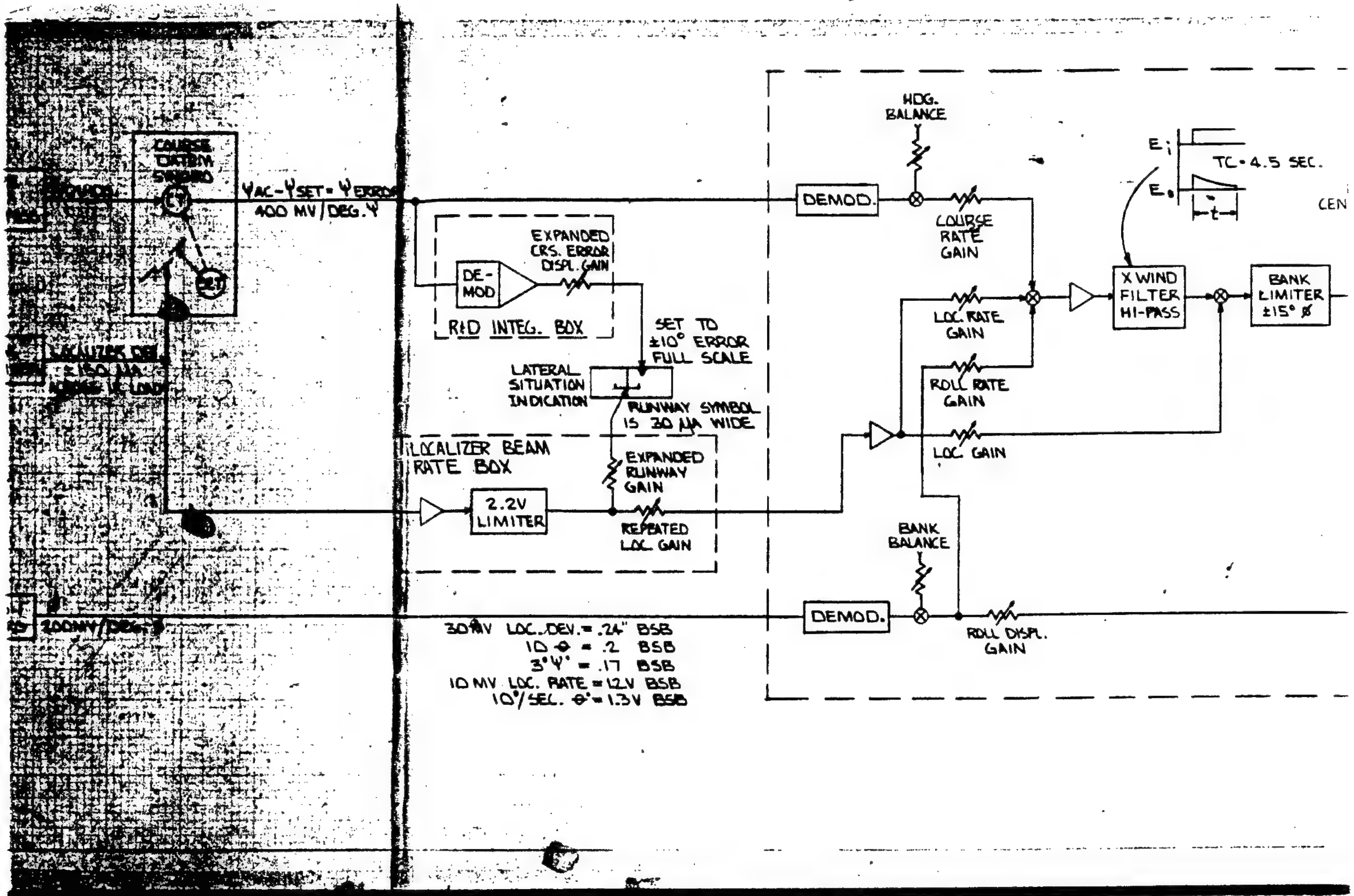
DE-MOD
EXPANDED COURSE ERROR DISPLAY
NAV. RECEIVER
±150 MA
SET TO BULL
±10° Ψ ERROR SCALE
RATE FIELD THRESHOLD = 1 μ/SEC. LOC. DEV.
LOC. RATE FIELD DRIVE EL CONTROLLER BOX
RUNWAY SYMBOL IS 30 MA WIDE
SIDESLIP COMPUTER
MOD.
RATE CRKT.
TC=.2 SEC.
EXPANDED RUNWAY GAIN
2.2V LIMIT
REPEATED LOCALIZER GAIN
TACAN COUPLE AC HDG.
RATE CRKT.
EXTERNAL LOC. RATE GAIN
LOCALIZER RATE BOX
TC=.2 SEC.
MD-1 GYRO
Ø
200 MV/DEG Ø
1



COURSE DATUM SYNCHRO
ΨAC-ΨSET = ΨERROR
400 MV/DEG.Ψ
SET
EXPANDED CRS. ERROR DISPL. GAIN
DE-MOD
R&D INTEG. BOX
SET TO ±10° ERROR FULL SCALE
LATERAL SITUATION INDICATION
RUNWAY SYMBOL IS 30 μA WIDE
LOCALIZER BEAM RATE BOX
EXPANDED RUNWAY GAIN
2.2V LIMITER
REPEATED LOC. GAIN
200MV/DEG.
30 MV LOC. DEV. = .24" BSB
10 Φ = .2 BSB
3°Ψ = .17 BSB
10 MV LOC. RATE = 1.2V BSB
10°/SEC. Φ = 1.3V BSB
HDG. BALANCE
DEMOD.
COURSE RATE GAIN
LOC. RATE GAIN
ROLL RATE GAIN
LOC. GAIN
BANK BALANCE
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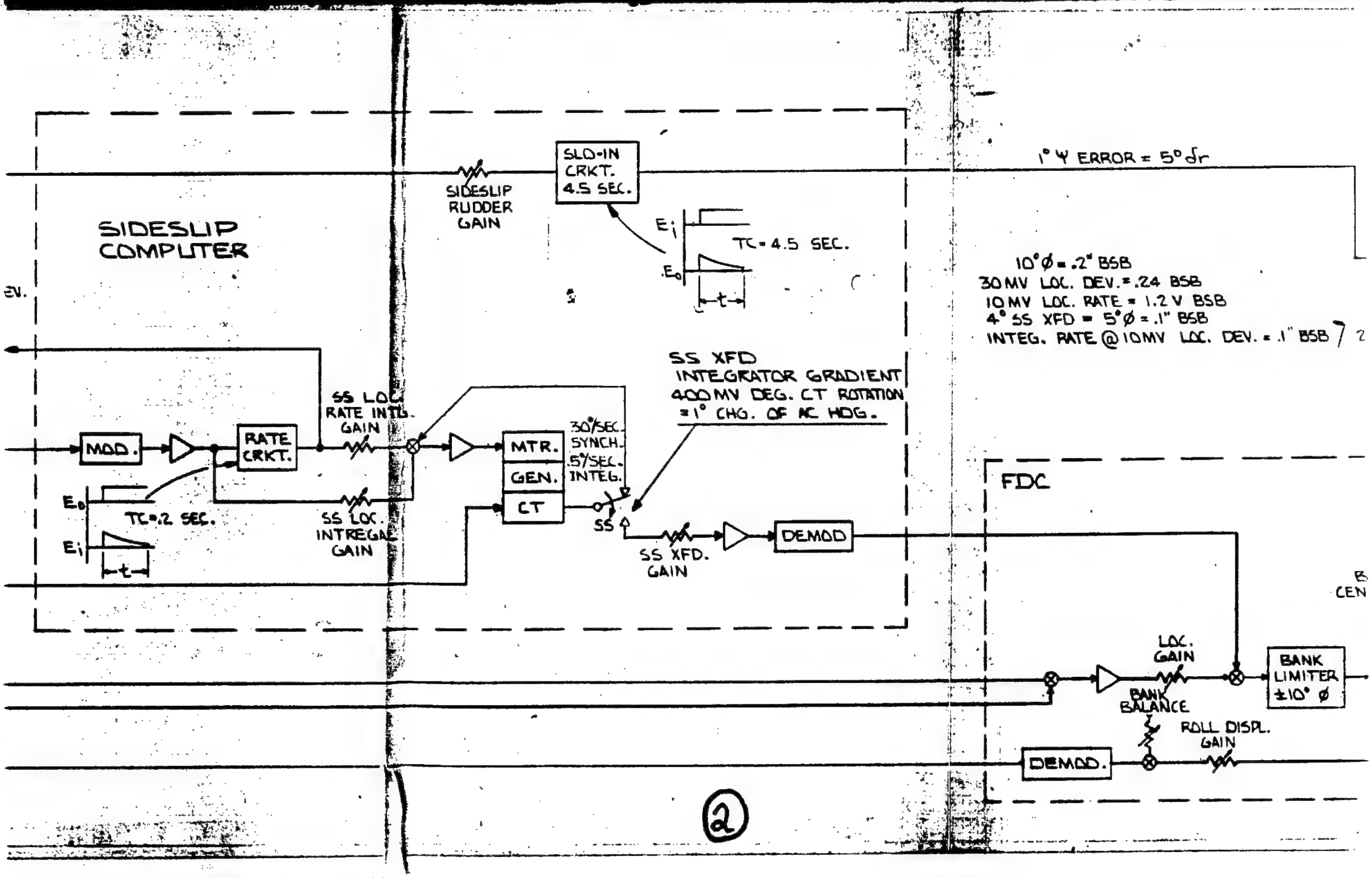


SIDESLIP COMPUTER
SIDESLIP RUDDER GAIN
SLO-IN CRKT. 4.5 SEC.
Ei
Eo
TC = 4.5 SEC.
t
1° Ψ ERROR = 5° δr
10°Φ = .2" BSB
30 MV LOC. DEV. = .24 BSB
10 MV LOC. RATE = 1.2 V BSB
4° SS XFD = 5°Φ = .1" BSB
INTEG. RATE @ 10MV LOC. DEV. = .1" BSB
EV.
MOD.
RATE CRKT.
SS LOC. RATE INTG. GAIN
SS LOC. INTREGAL GAIN
TC = .2 SEC.
Eo
Ei
MTR.
GEN.
CT
30°/SEC. SYNCH.
.5°/SEC. INTEG.
SS
SS XFD INTEGRATOR GRADIENT 400 MV DEG. CT ROTATION = 1° CHG. OF AC HDG.
SS XFD. GAIN
DEMOD
FDC
B CEN
LOC. GAIN
BANK BALANCE
BANK LIMITER ±10° Φ
ROLL DISPL. GAIN
DEMOD.

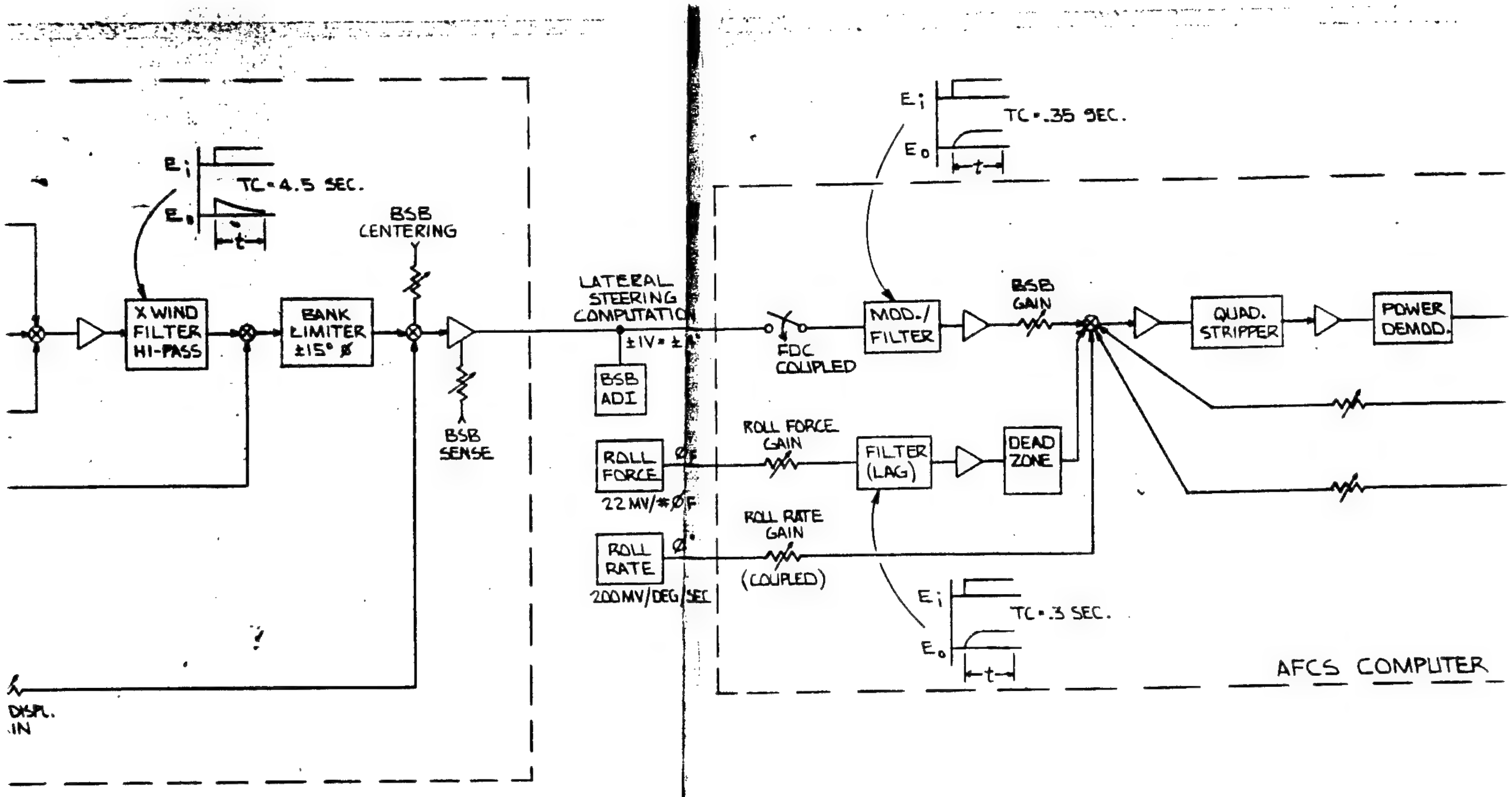
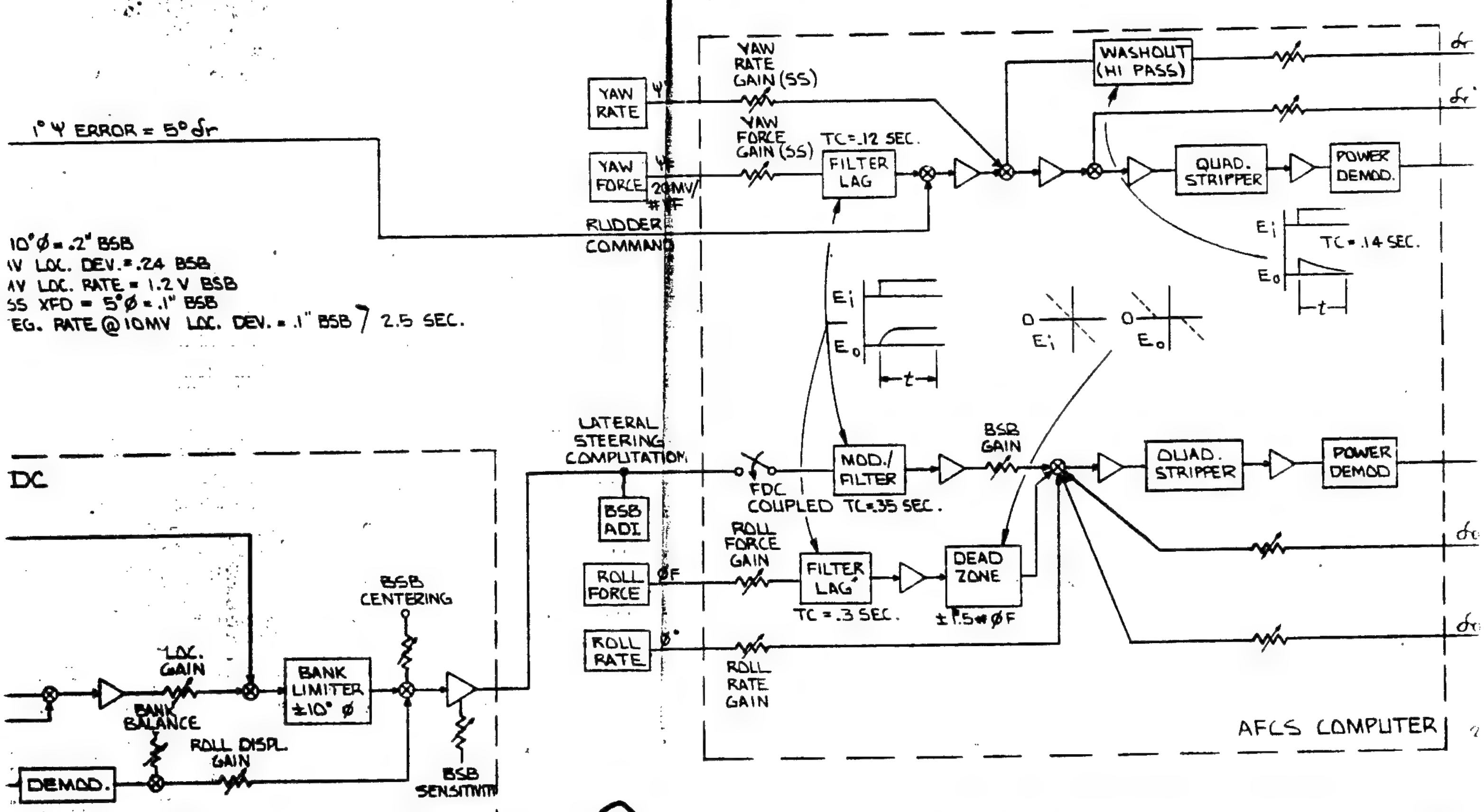


Fig. 47: Lateral Track Mode Signal Flow and Computation Track M



3

Fig. 48: Lateral Track Mode Signal Flow and Computation – Track Mode P

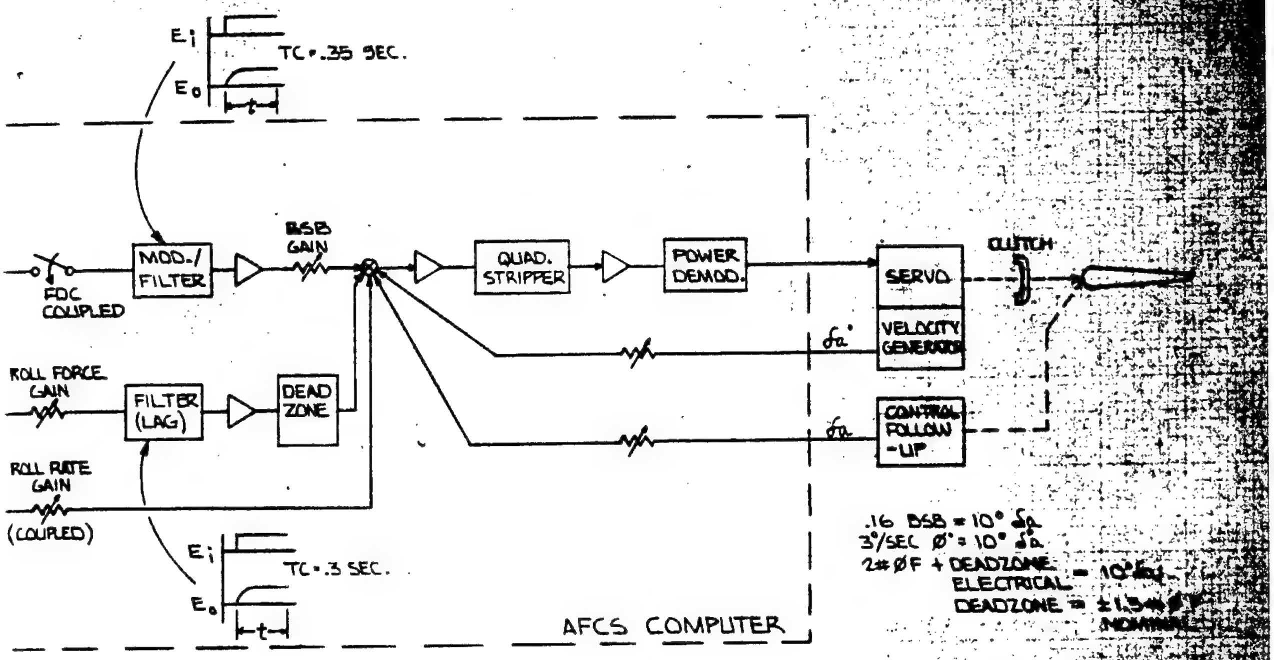


Fig. 47: Lateral Track Mode Signal Flow and Computation Track Mode Plus Initial

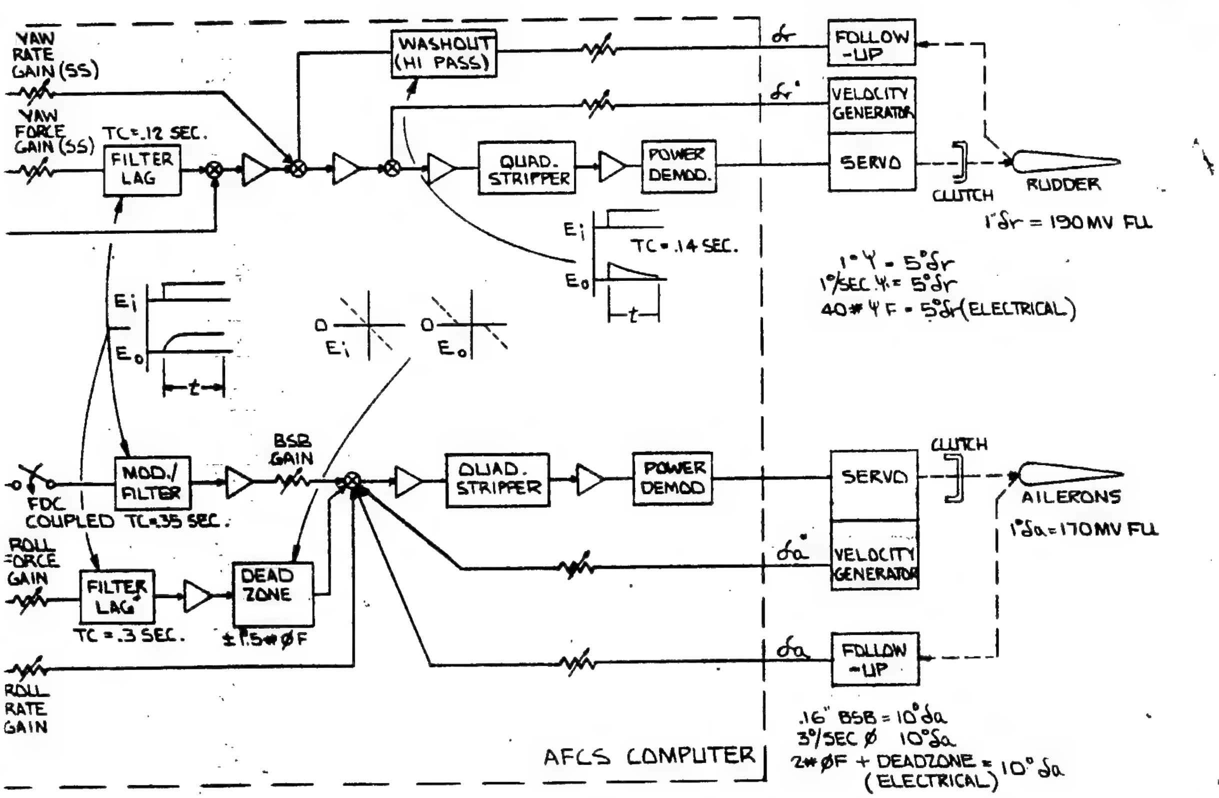
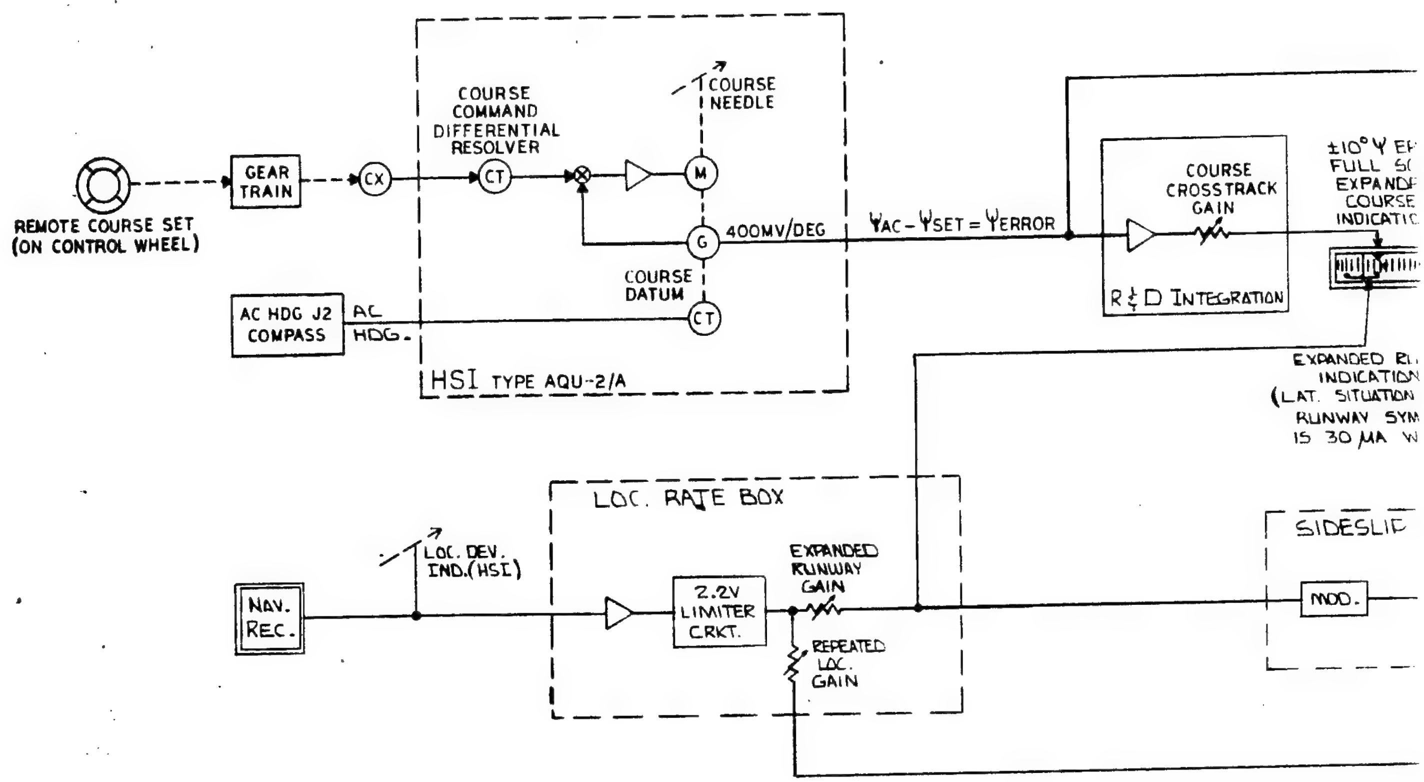
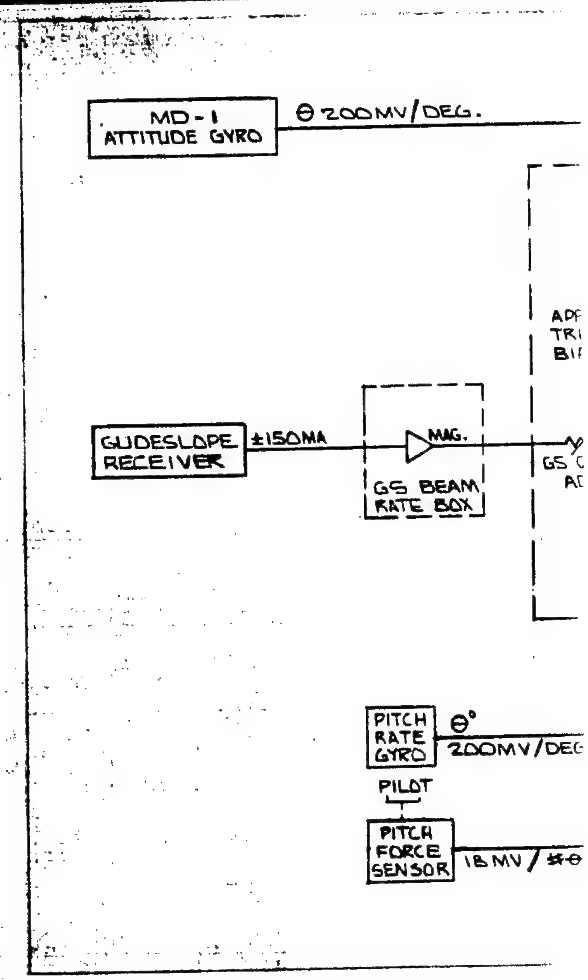


Fig. 48: Lateral Track Mode Signal Flow and Computation – Track Mode Plus Final (Side-Slip Enabled)

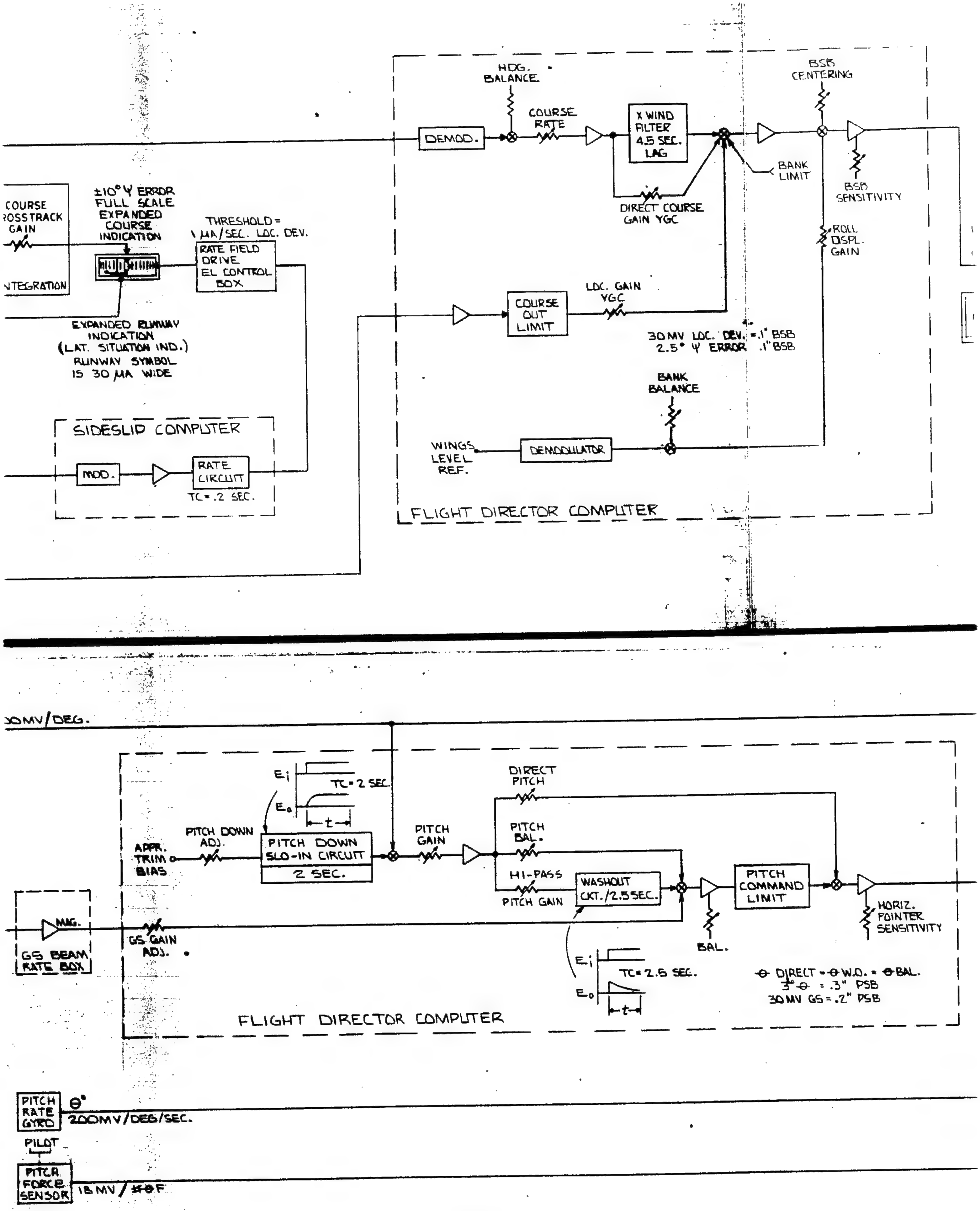
4



COURSE COMMAND DIFFERENTIAL RESOLVER
COURSE NEEDLE
GEAR TRAIN
CX
CT
M
G
CT
REMOTE COURSE SET (ON CONTROL WHEEL)
400MV/DEG
ΨAC – ΨSET = ΨERROR
COURSE CROSSTRACK GAIN
R & D INTEGRATION
COURSE DATUM
AC HDG J2 COMPASS
AC HDG.
HSI TYPE AQU-2/A
LOC. RATE BOX
LOC. DEV. IND.(HSI)
NAV. REC.
2.2V LIMITER CRKT.
EXPANDED RUNWAY GAIN
REPEATED LOC. GAIN
MOD.



MD-1 ATTITUDE GYRO
θ 200MV/DEG.
GLIDESLOPE RECEIVER
±150MA
MAG.
GS BEAM RATE BOX
PITCH RATE GYRO
θ°
PILOT
PITCH FORCE SENSOR
18 MV /



HDG. BALANCE
COURSE RATE
X WIND FILTER 4.5 SEC. LAG
BSB CENTERING
DEMOD.
BANK LIMIT
BSB SENSITIVITY
DIRECT COURSE GAIN YGC
ROLL DSPL. GAIN
COURSE CROSSTRACK GAIN
INTEGRATION
±10° Ψ ERROR FULL SCALE EXPANDED COURSE INDICATION
THRESHOLD = 1 μA/SEC. LOC. DEV.
RATE FIELD DRIVE EL CONTROL BOX
EXPANDED RUNWAY INDICATION (LAT. SITUATION IND.) RUNWAY SYMBOL IS 30 μA WIDE
COURSE OUT LIMIT
LOC. GAIN YGC
30 MV LOC. DEV. = .1" BSB
2.5° Ψ ERROR .1" BSB
BANK BALANCE
SIDESLIP COMPUTER
MOD.
RATE CIRCUIT
TC = .2 SEC.
WINGS LEVEL REF.
DEMODULATOR
FLIGHT DIRECTOR COMPUTER
30 MV/DEG.
E_i
TC = 2 SEC.
E_o
t
DIRECT PITCH
PITCH DOWN ADJ.
PITCH GAIN
PITCH BAL.
APPR. TRIM BIAS
PITCH DOWN SLO-IN CIRCUIT
2 SEC.
HI-PASS PITCH GAIN
WASHOUT CKT./2.5 SEC.
PITCH COMMAND LIMIT
HORIZ. POINTER SENSITIVITY
MAG.
GS BEAM RATE BOX
GS GAIN ADJ.
BAL.
E_i
TC = 2.5 SEC.
E_o
t
θ DIRECT = θ W.O. = θ BAL.
3° θ = .3" PSB
30 MV GS = .2" PSB
FLIGHT DIRECTOR COMPUTER
PITCH RATE GYRO
θ̇
200 MV/DEG/SEC.
PILOT
PITCH FORCE SENSOR
18 MV/ #F

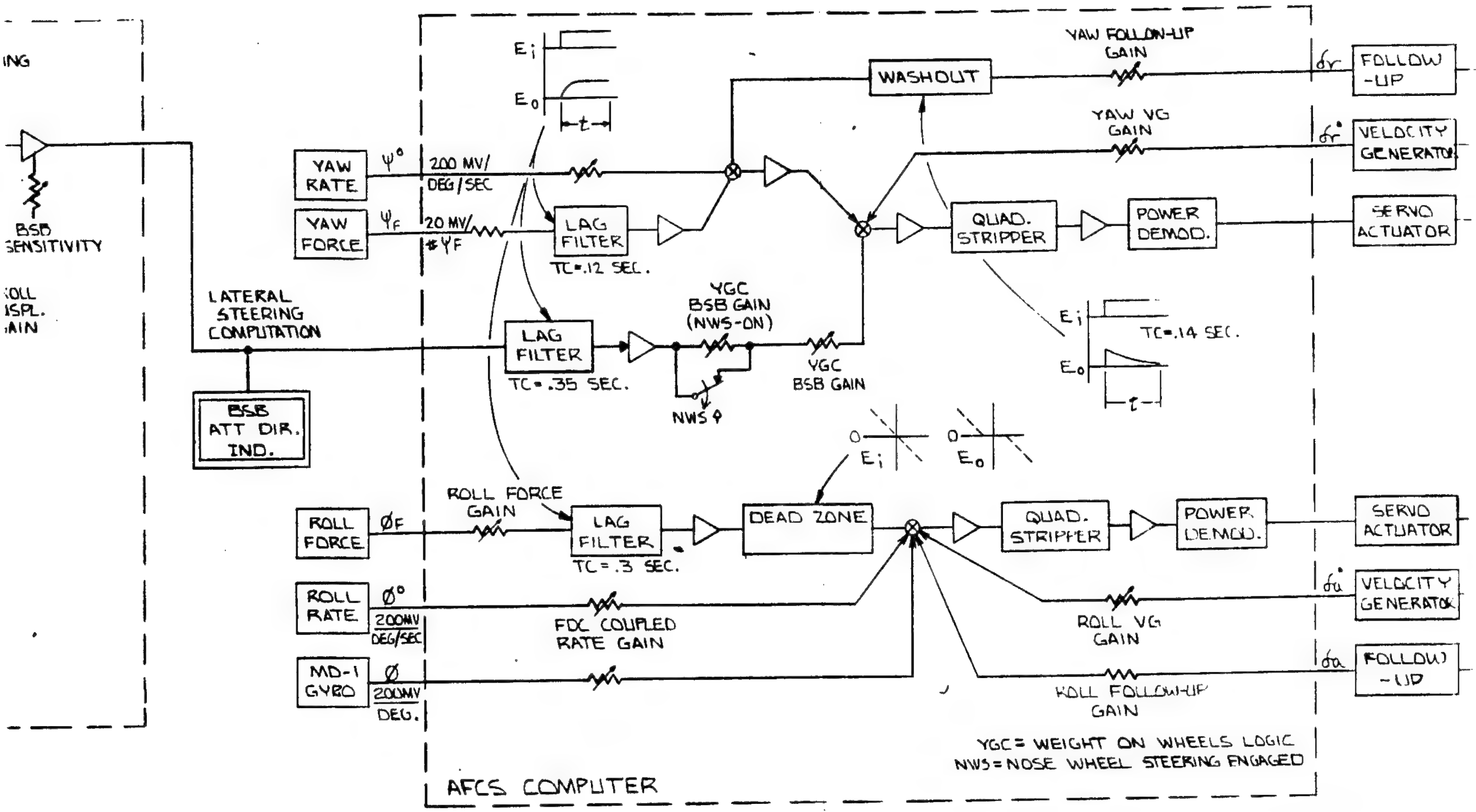


Fig. 49: Lateral YGC Signal Flow and Computation

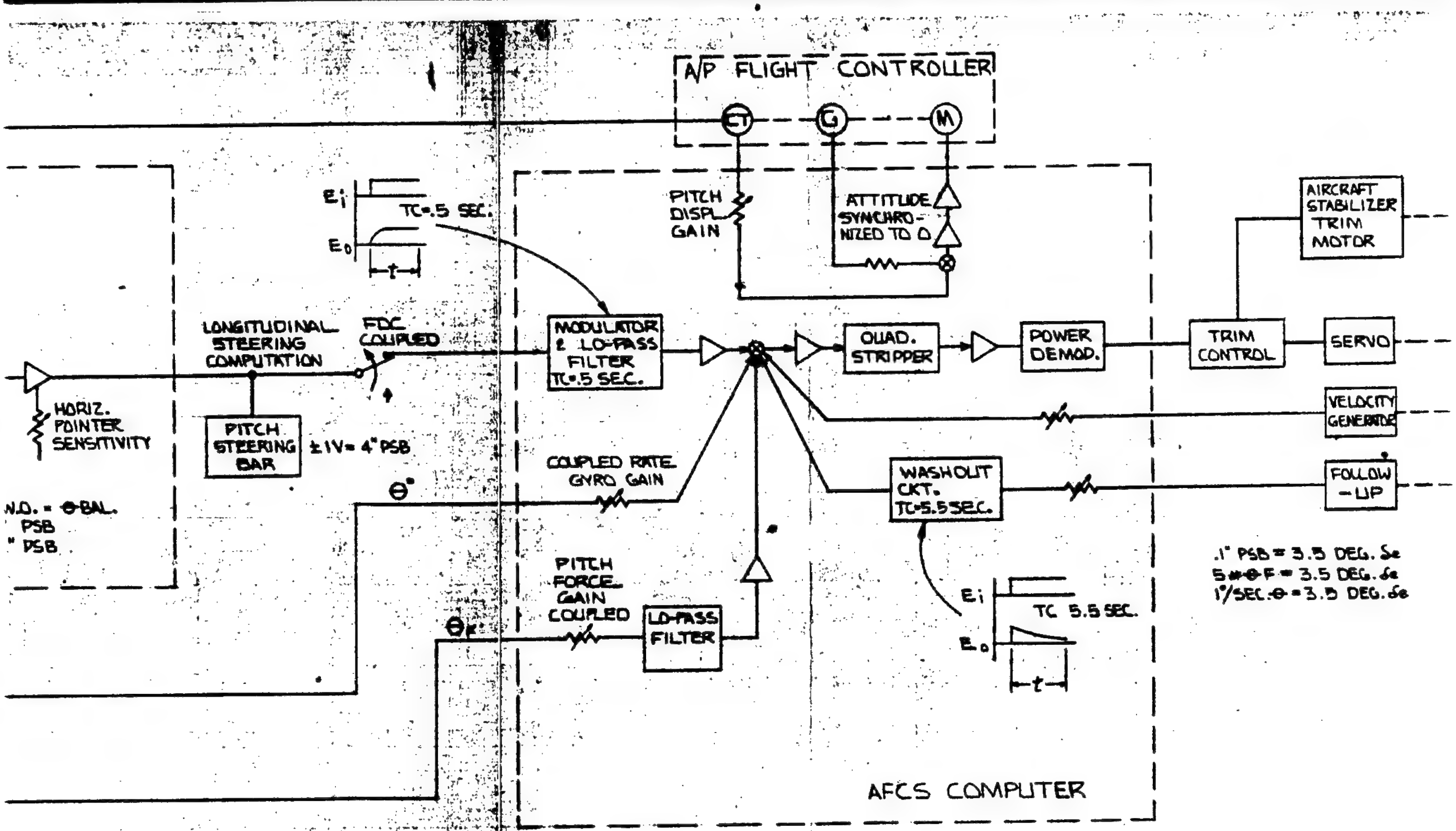


Fig. 50: Longitudinal Signal Flow and Computation ILS, GS Capture, Landing

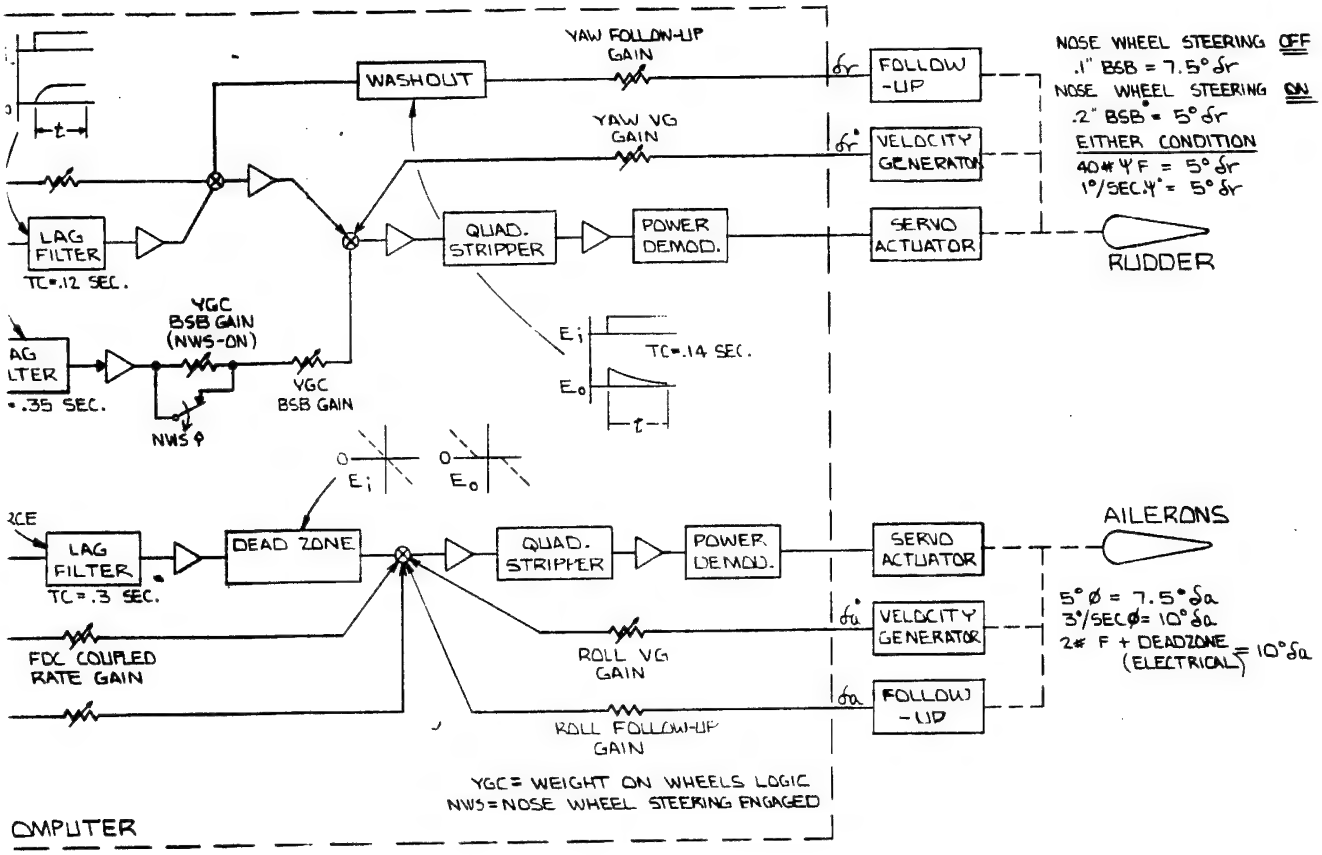


Fig. 49: Lateral YGC Signal Flow and Computation

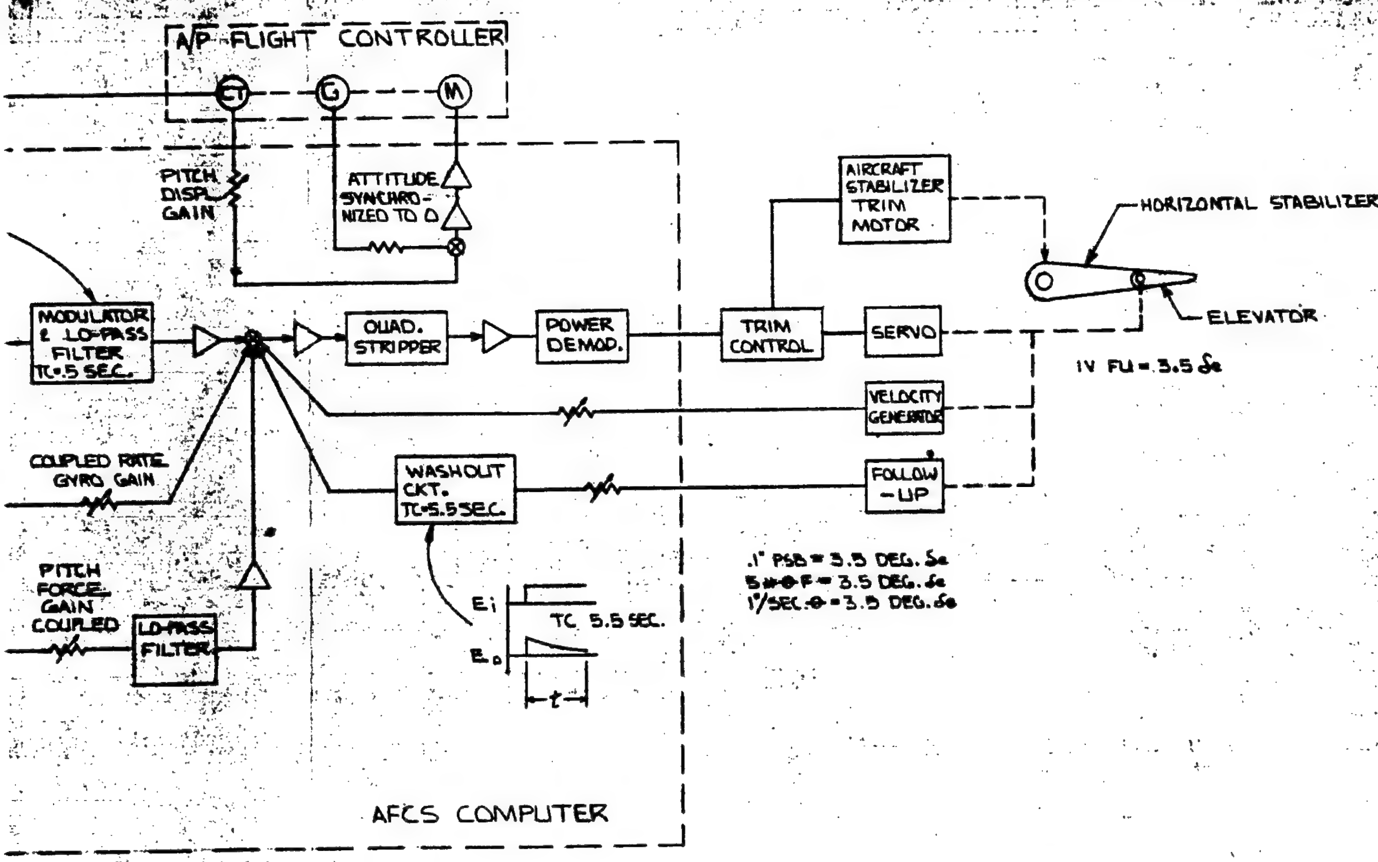


Fig. 50: Longitudinal Signal Flow and Computation ILS, GS Capture Landing Sequence at "Initial"

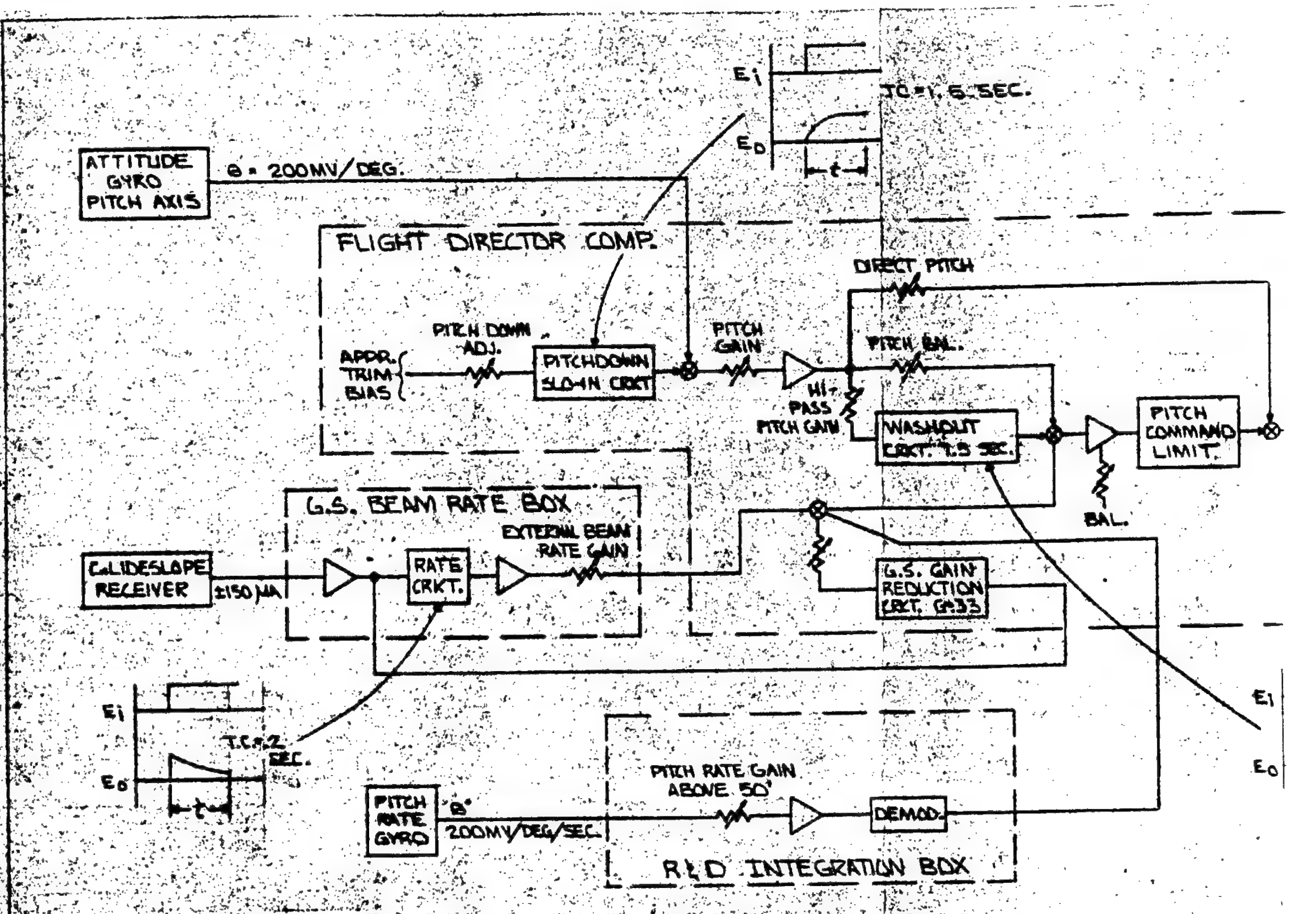


Fig. 51: Longitudinal Signal Flow and

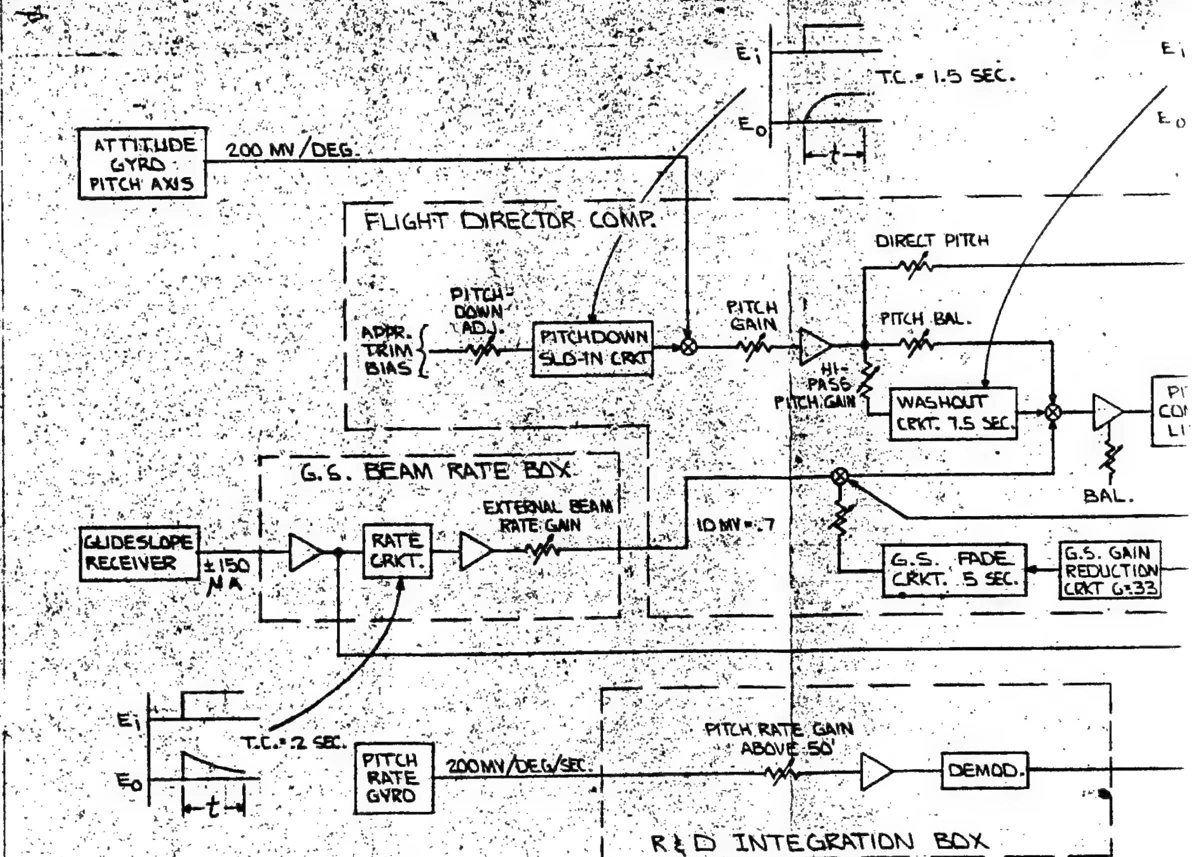


Fig. 52: Longitudinal Signal F

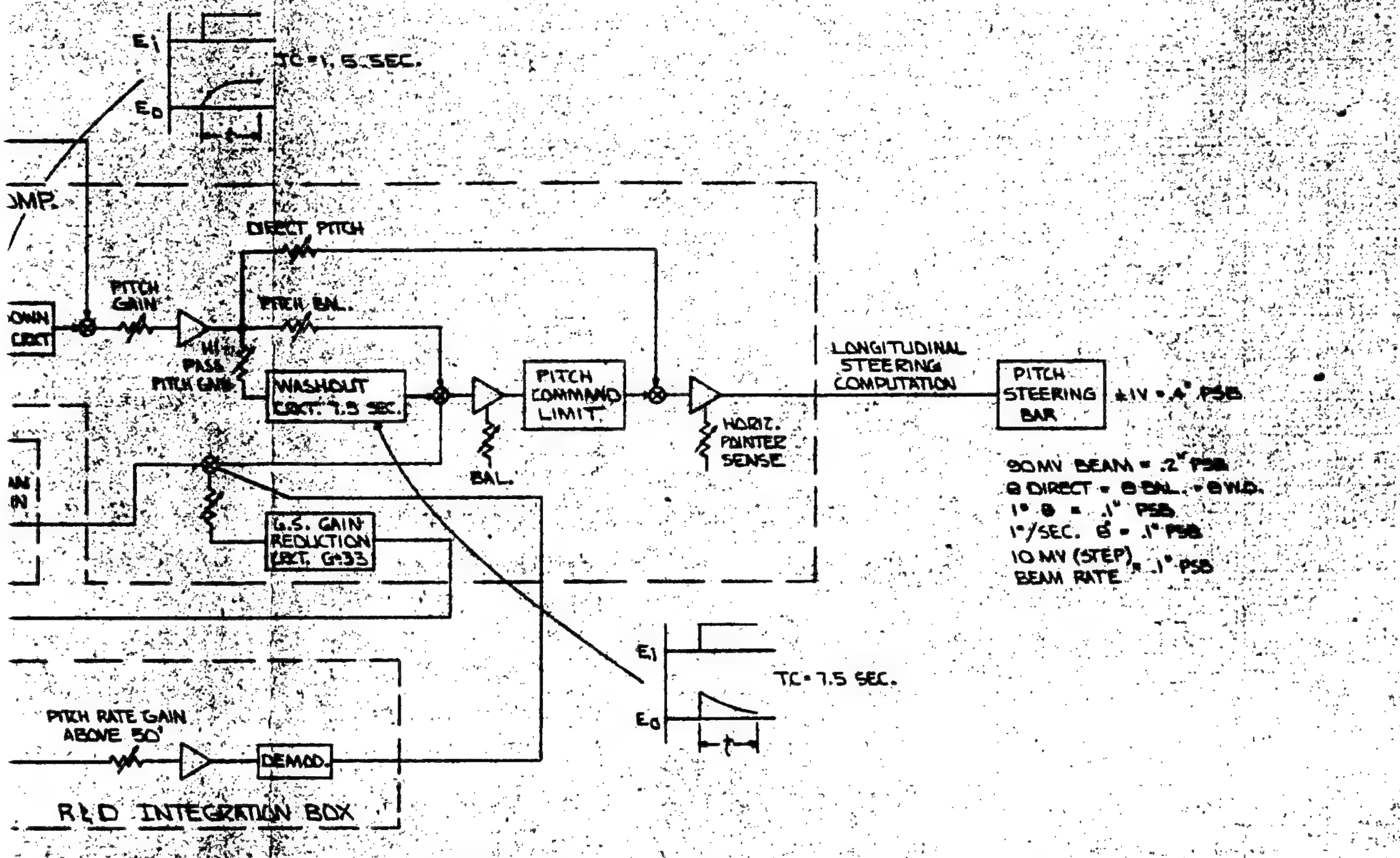


Fig. 51: Longitudinal Signal Flow and Computation ILS Approach, Track and Final

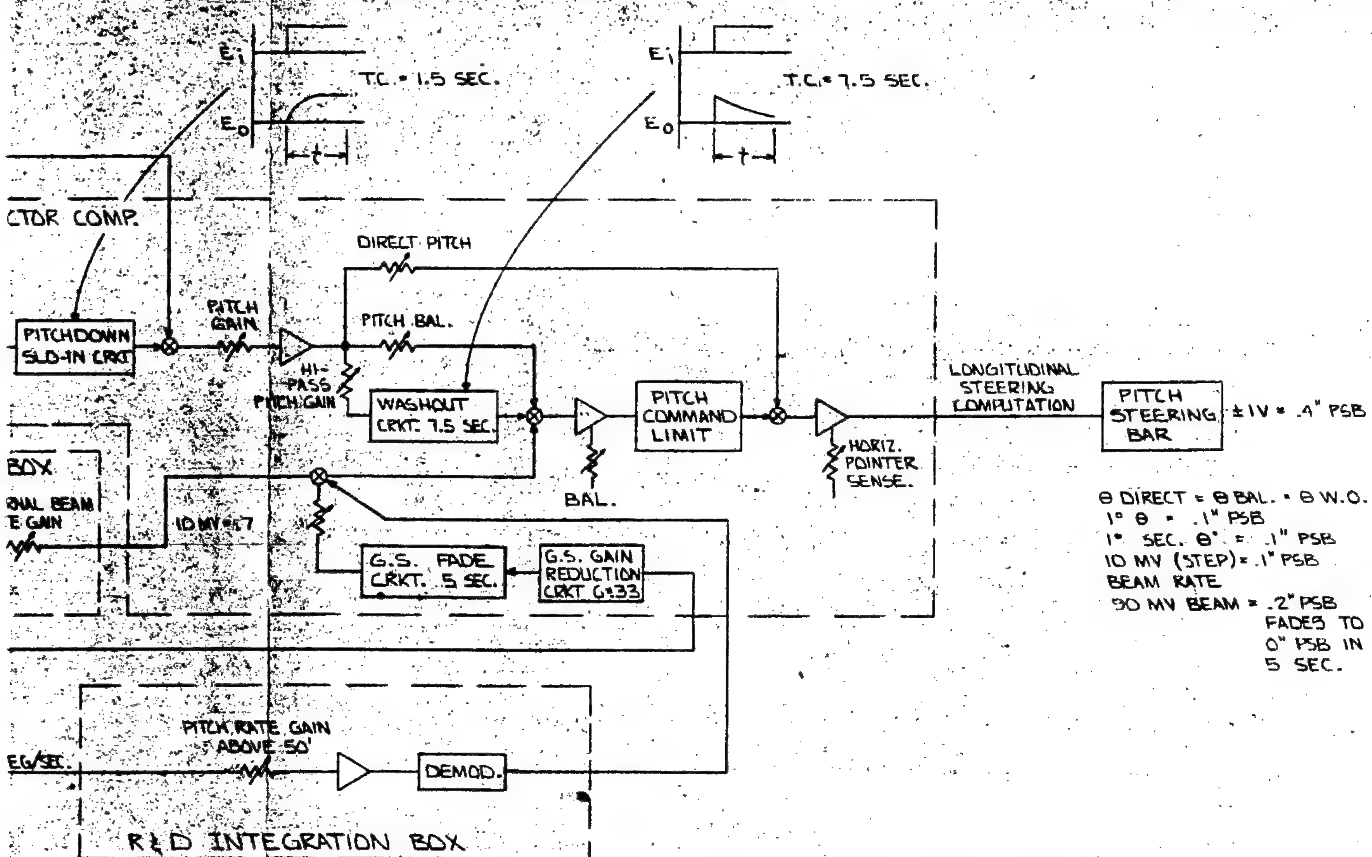


Fig. 52: Longitudinal Signal Flow and Computation ILS Approach, Track and 100'

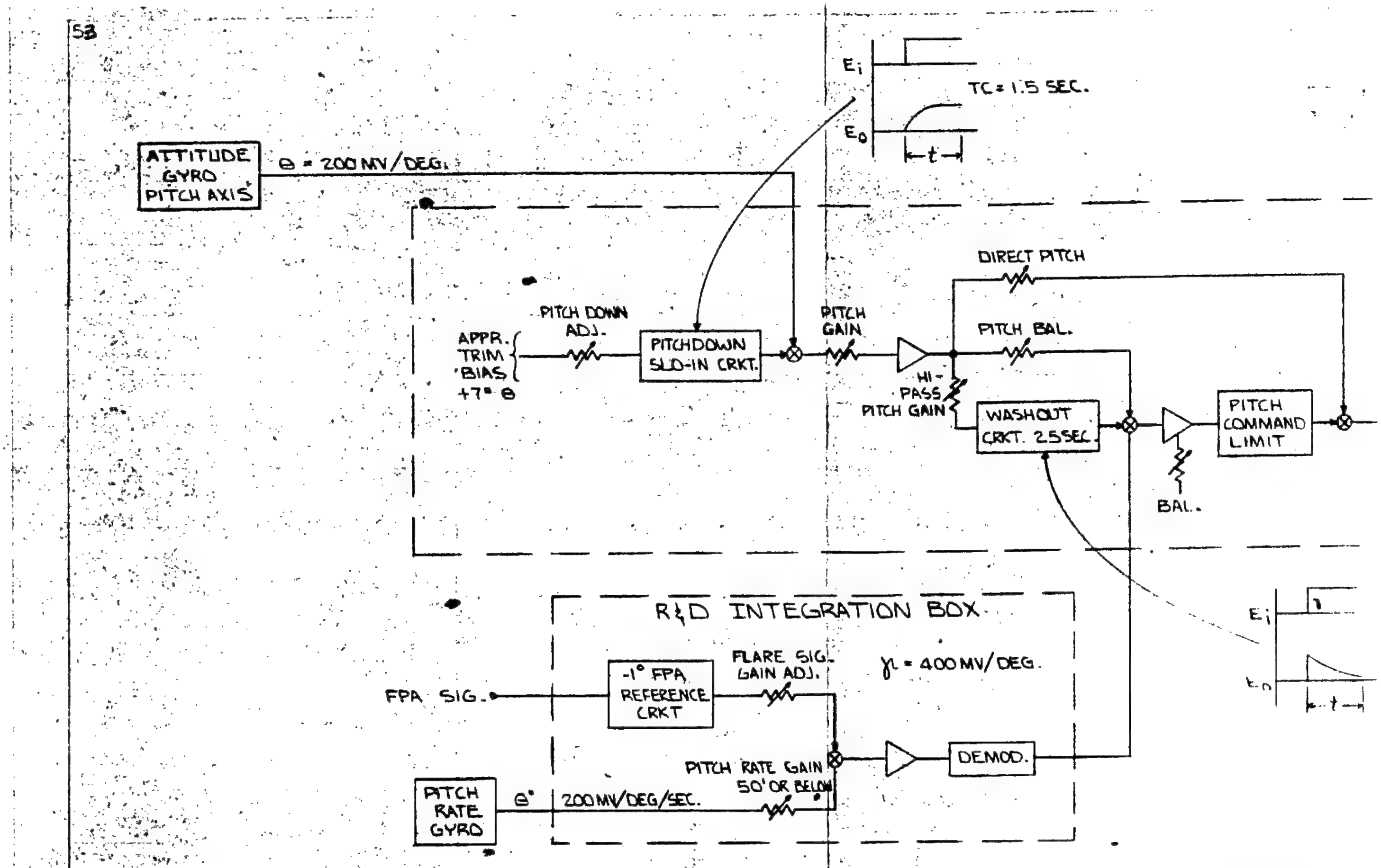


Fig. 53: Longitudinal Signal Fl

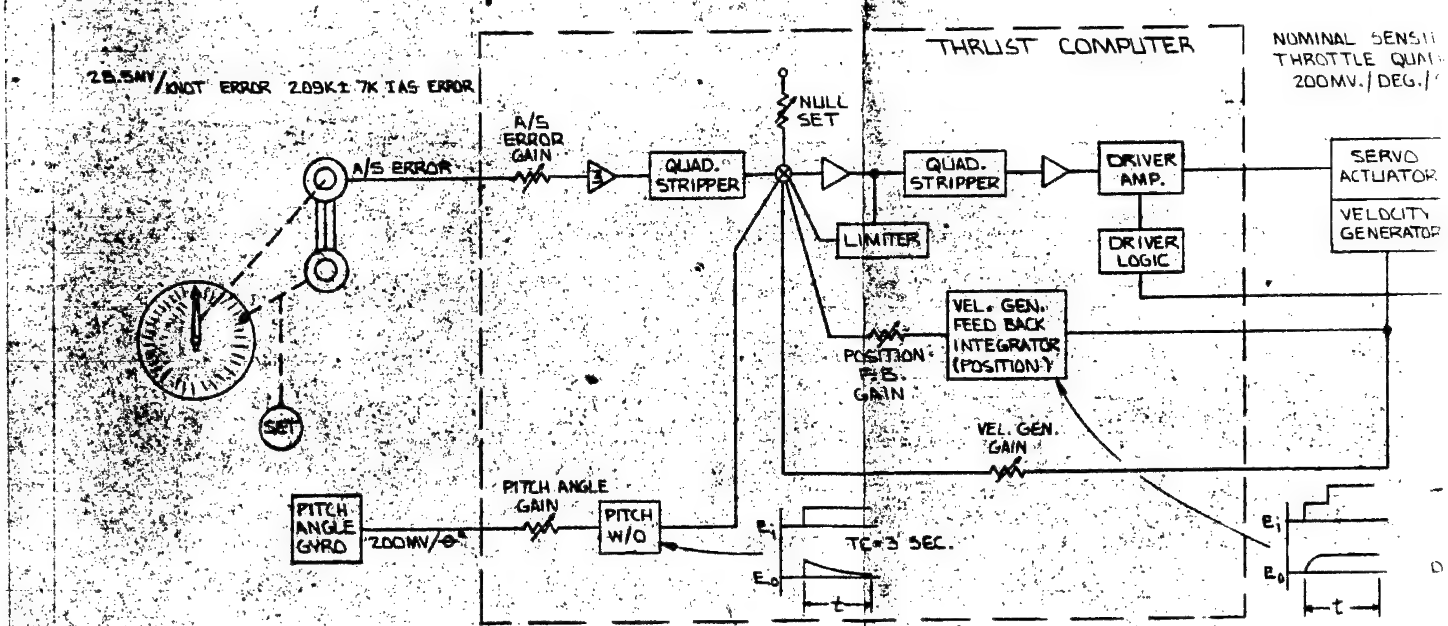


Fig. 54: Auto Throttle – Speed Command and Indicator S

1

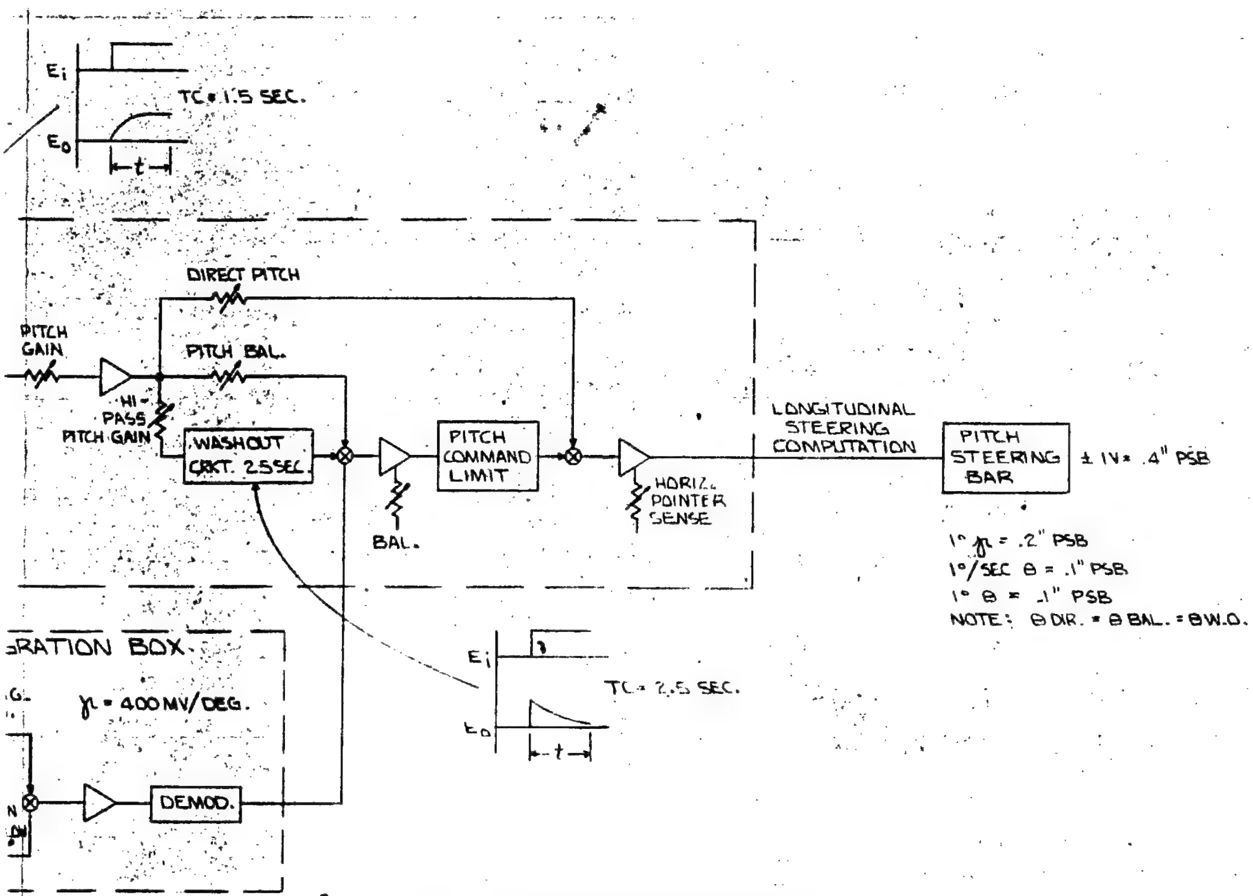


Fig. 53: Longitudinal Signal Flow and Computation Flare

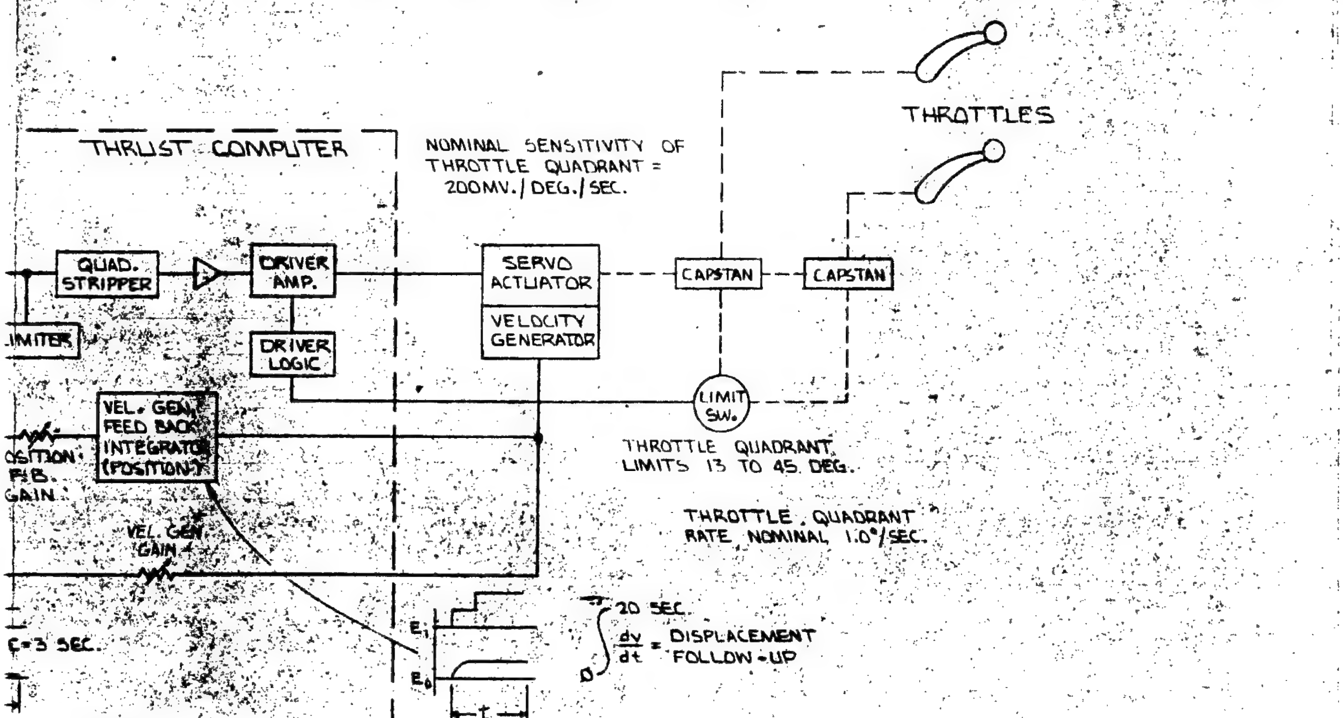


Fig. 54: Auto Throttle — Speed Command and Indicator System — IAS Hold Mode

2

102

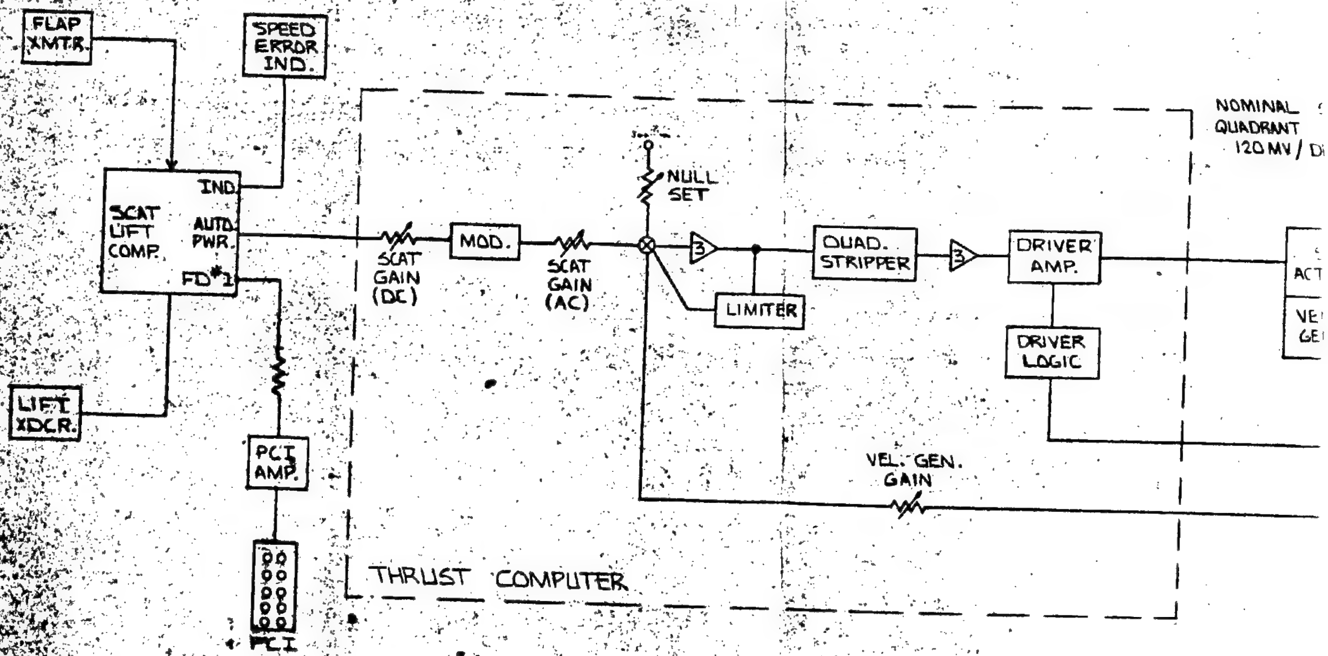


Fig. 55: Auto Throttle – Speed Command and Indic.

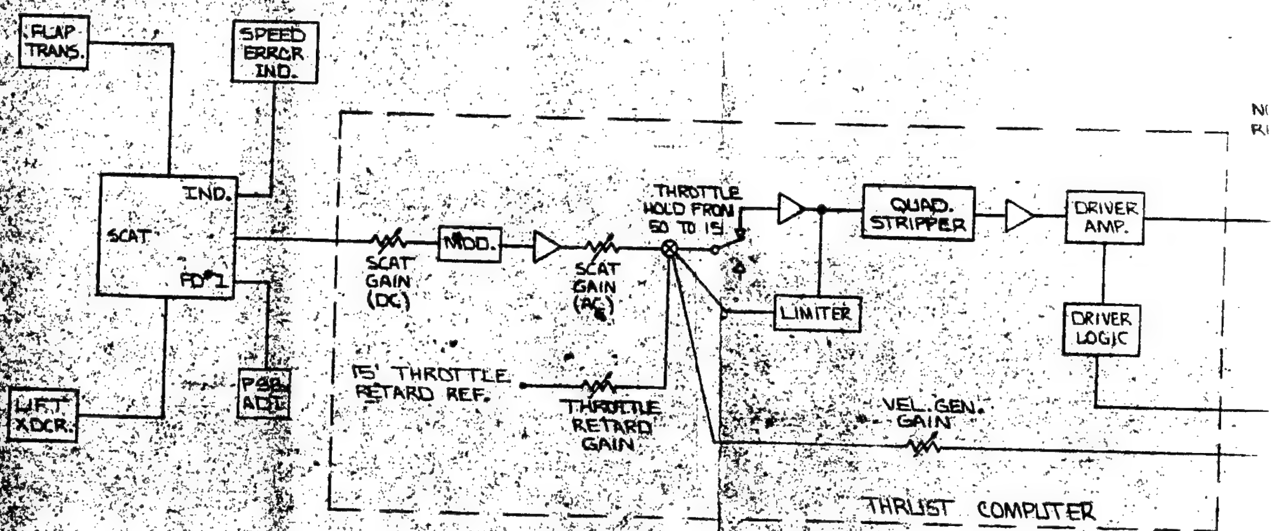


Fig. 56: Auto Throttle – speed Command an

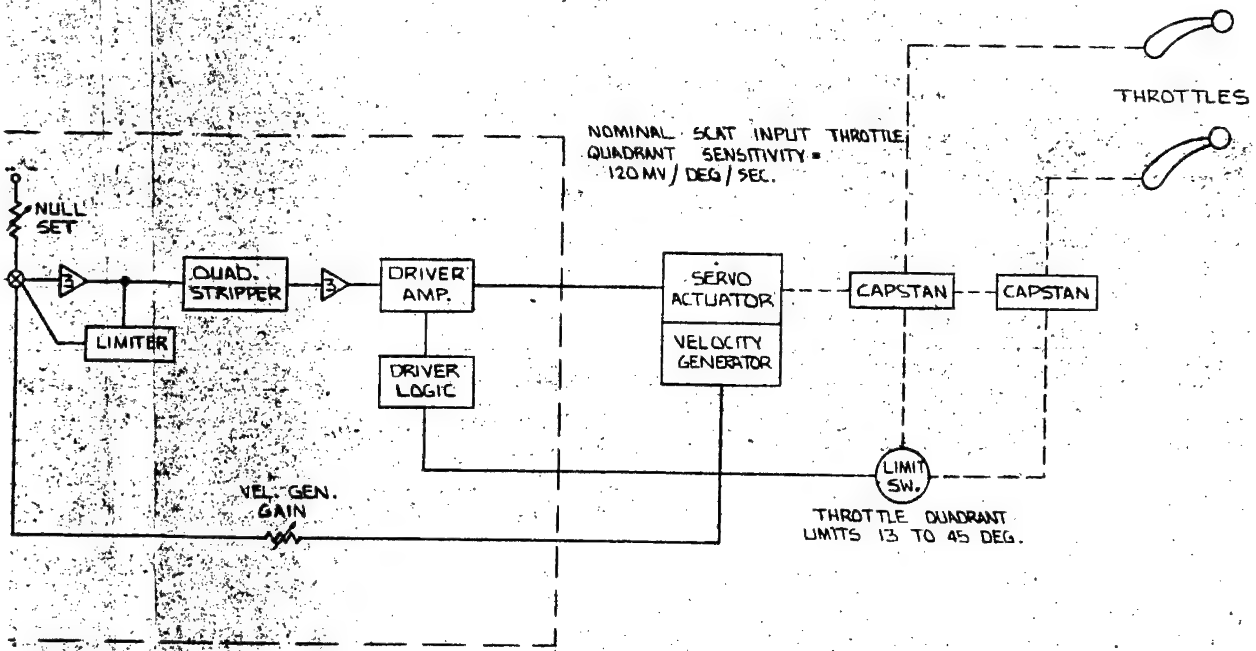


Fig. 55: Auto Throttle – Speed Command and Indicator System – SCAT/Approach Mode

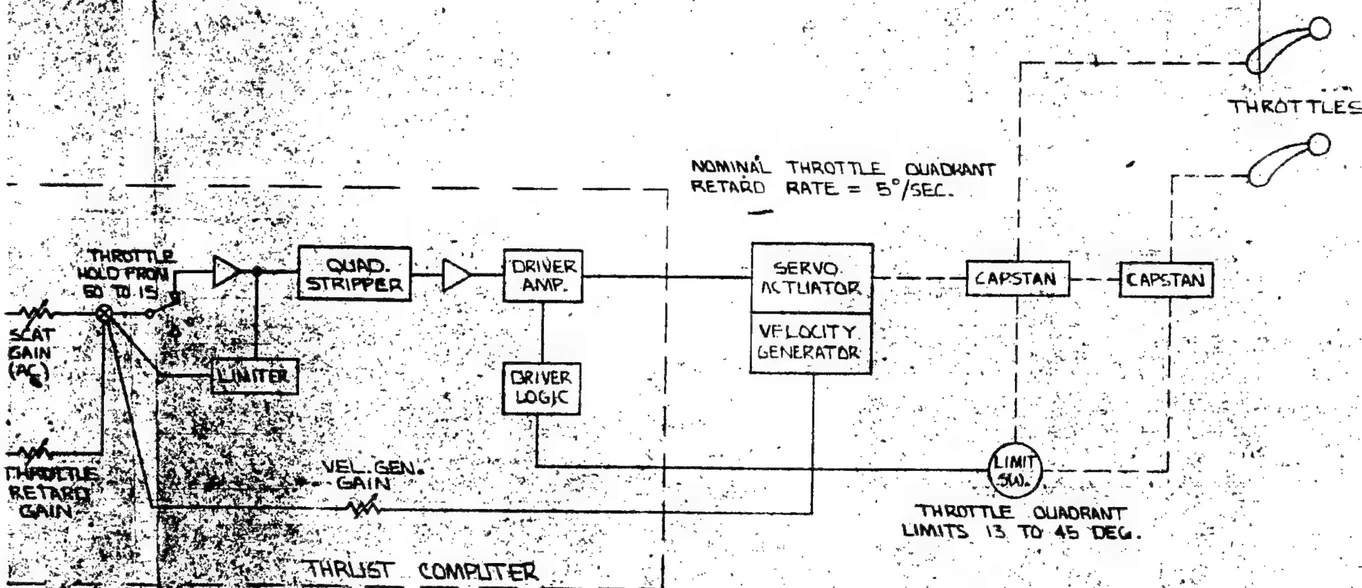


Fig. 56: Auto Throttle – speed Command and indicator System – SCAT/Flare Mode

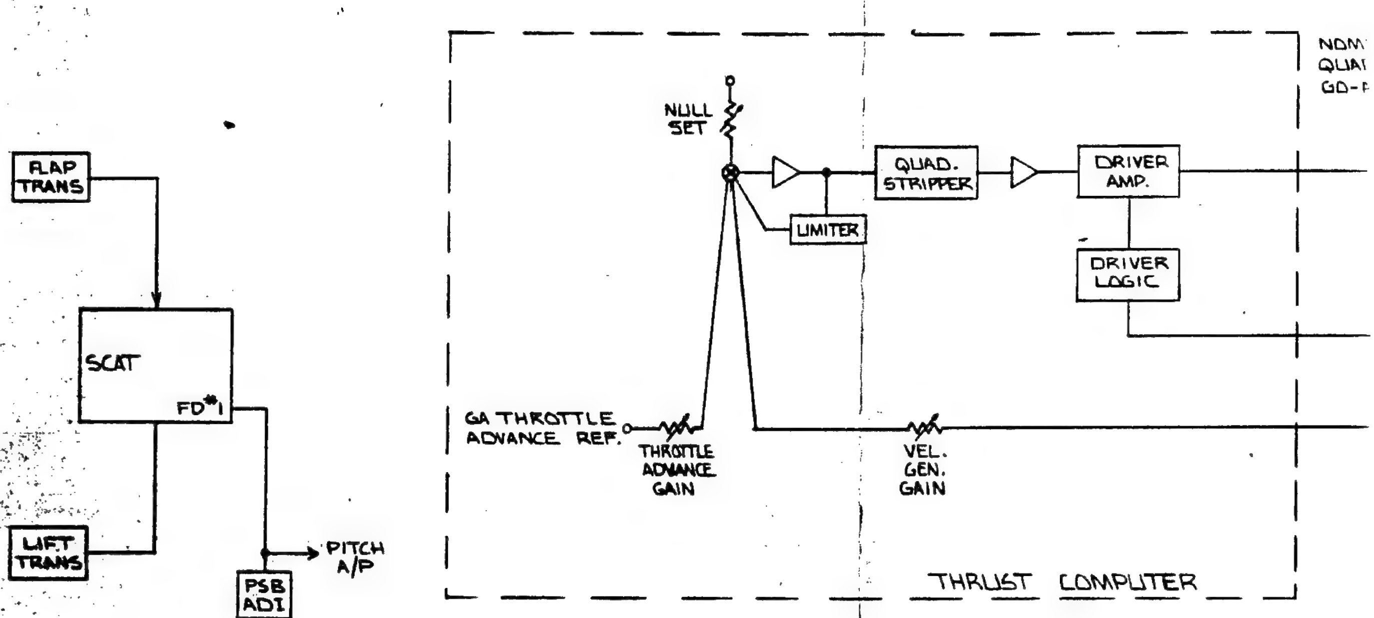


Fig. 57: Auto Throttle – Speed Comm

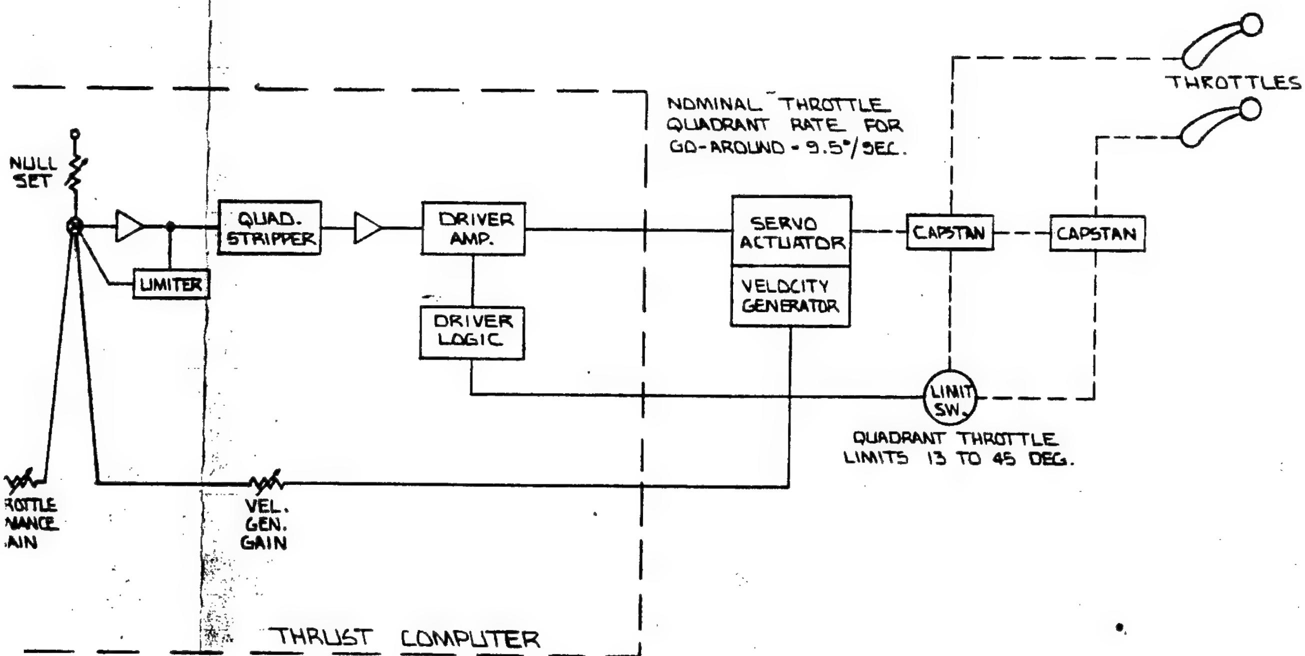
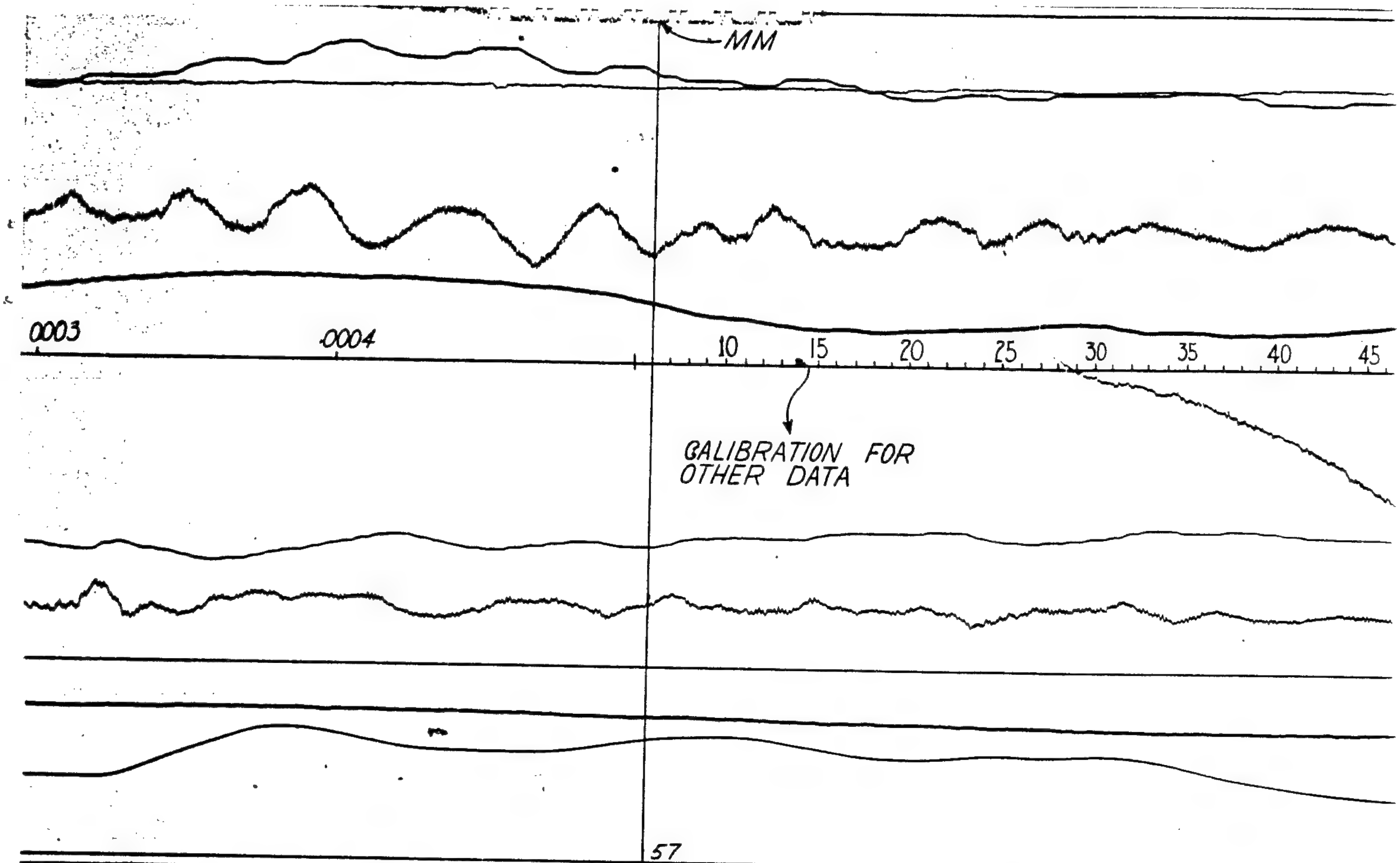
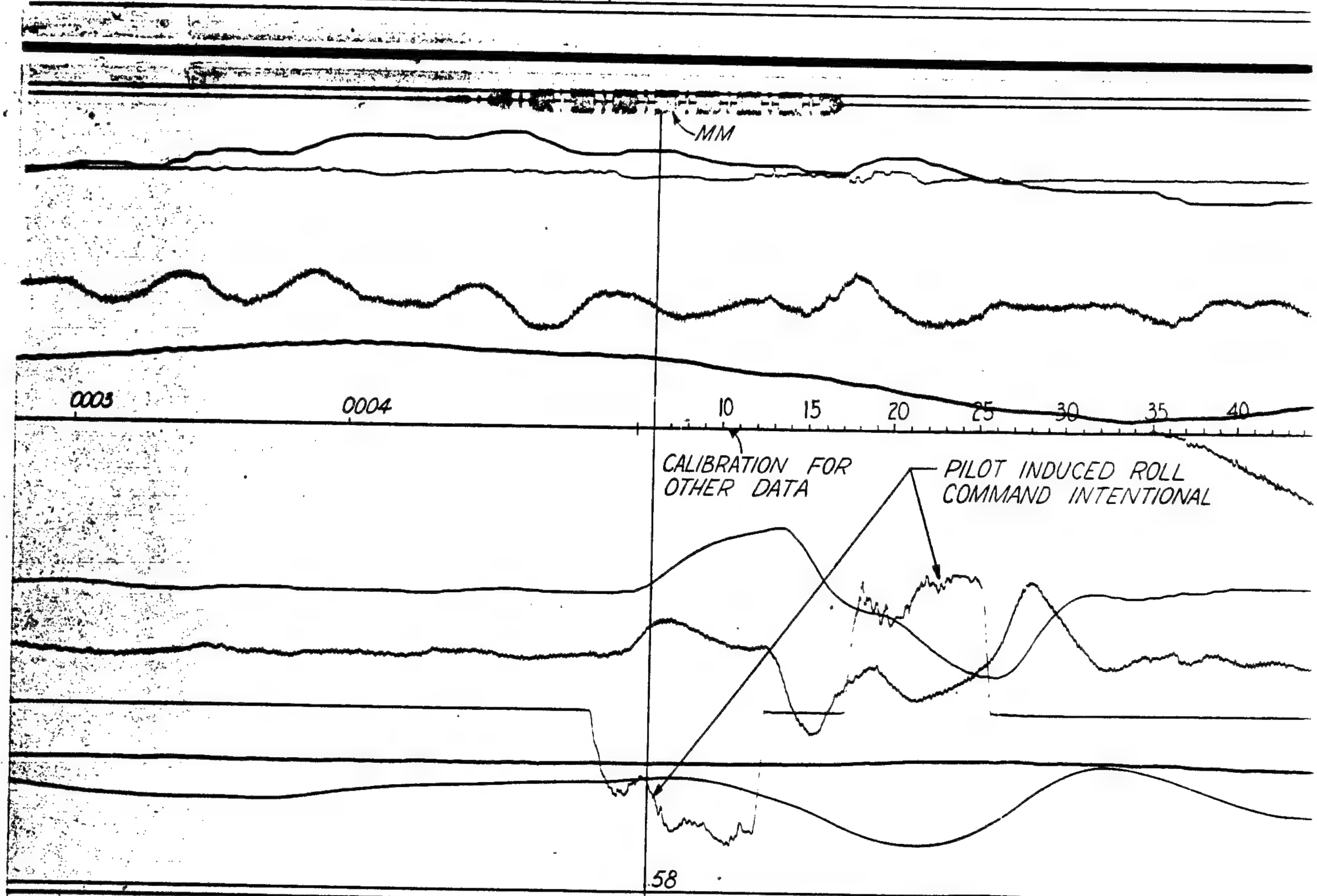


Fig. 57: Auto Throttle – Speed Command and Indicator System – SCAT/GA Mode

2

105


MM
0003
0004
10
15
20
25
30
35
40
45
CALIBRATION FOR OTHER DATA
57


MM
0003
0004
10
15
20
25
30
35
40
CALIBRATION FOR OTHER DATA
PILOT INDUCED ROLL COMMAND INTENTIONAL
58

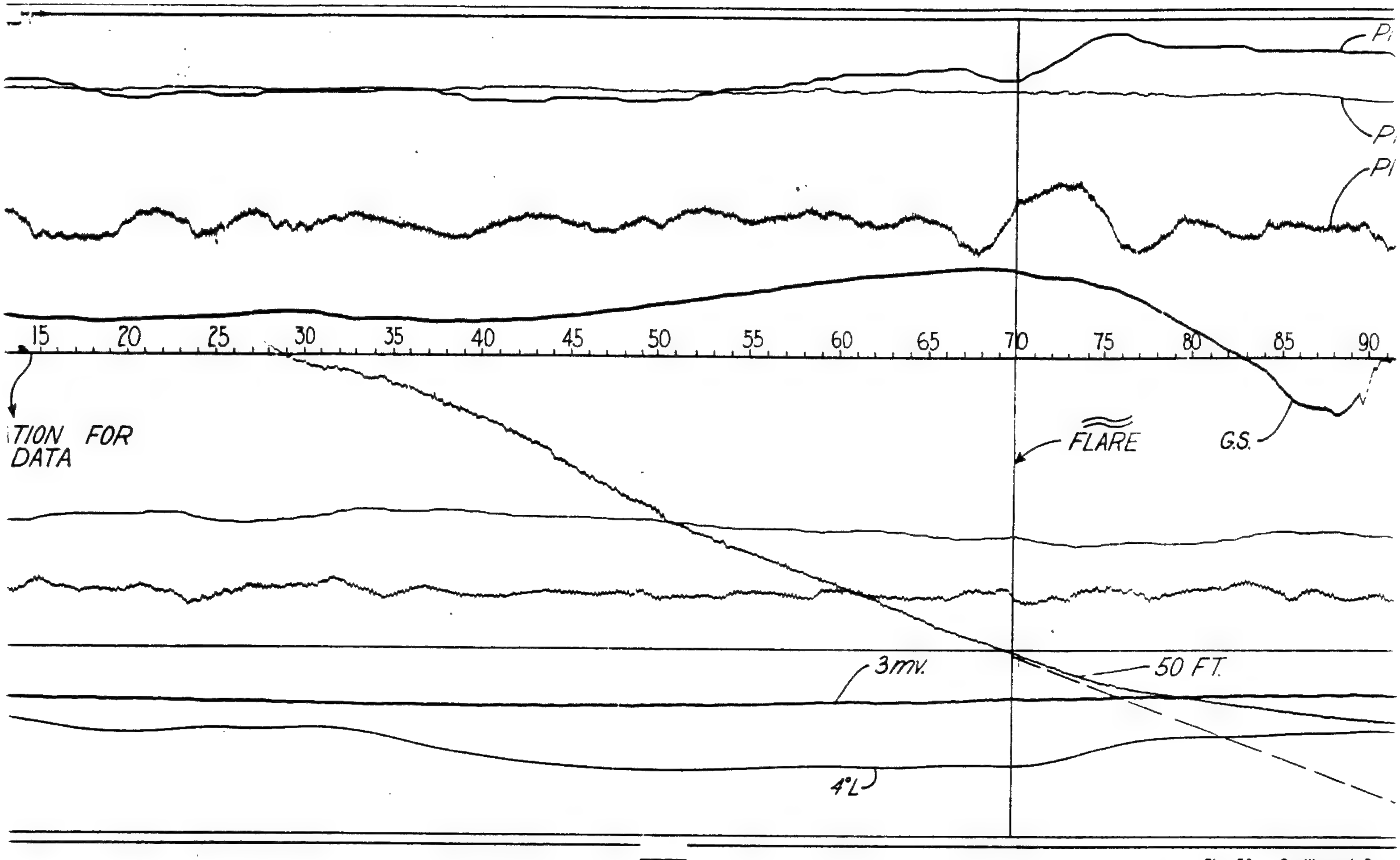


Fig. 58: Oscillograph Reco

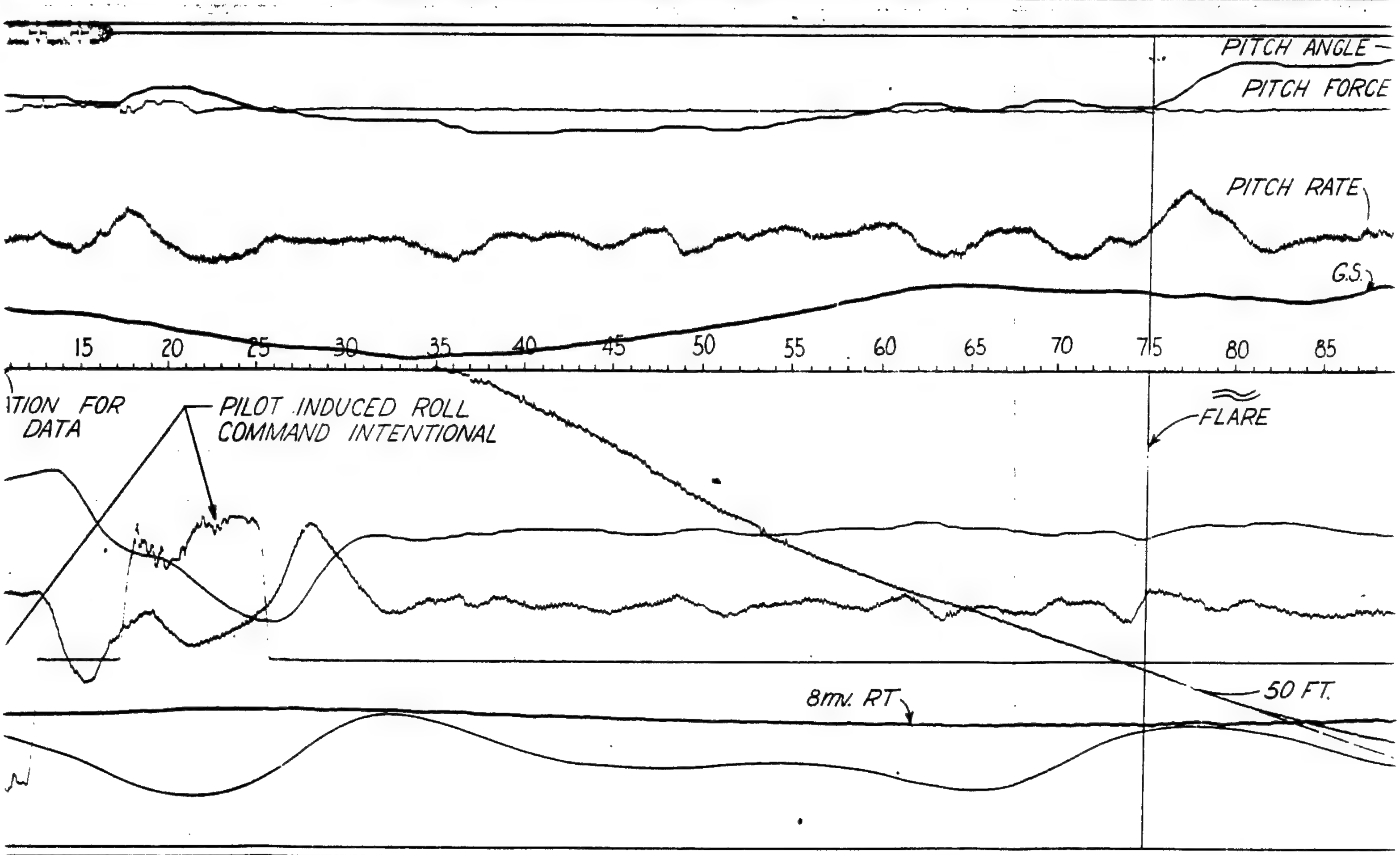


Fig. 59 Oscillograph Recordir

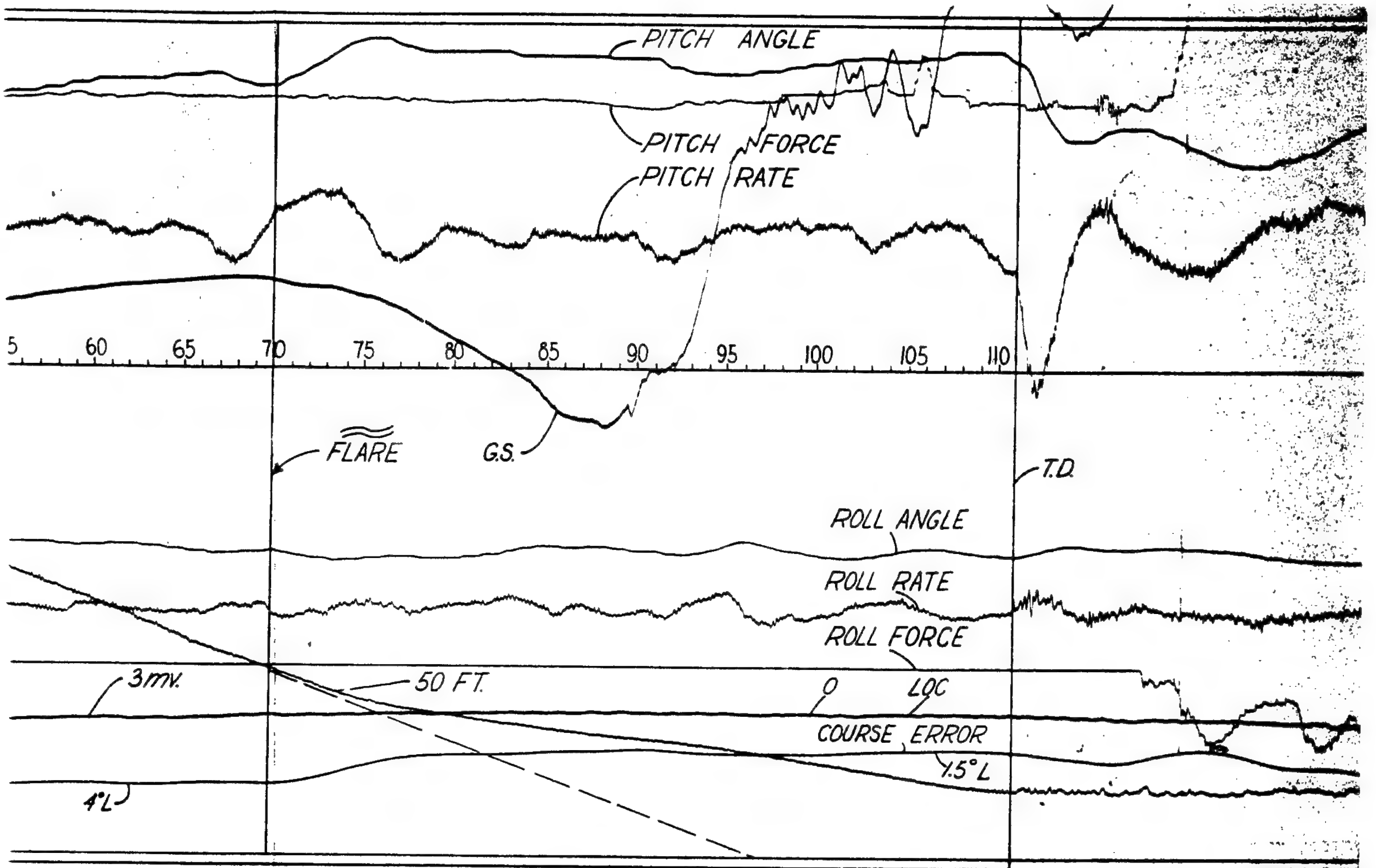


Fig. 58: Oscillograph Recording – Mather AFB, California #1

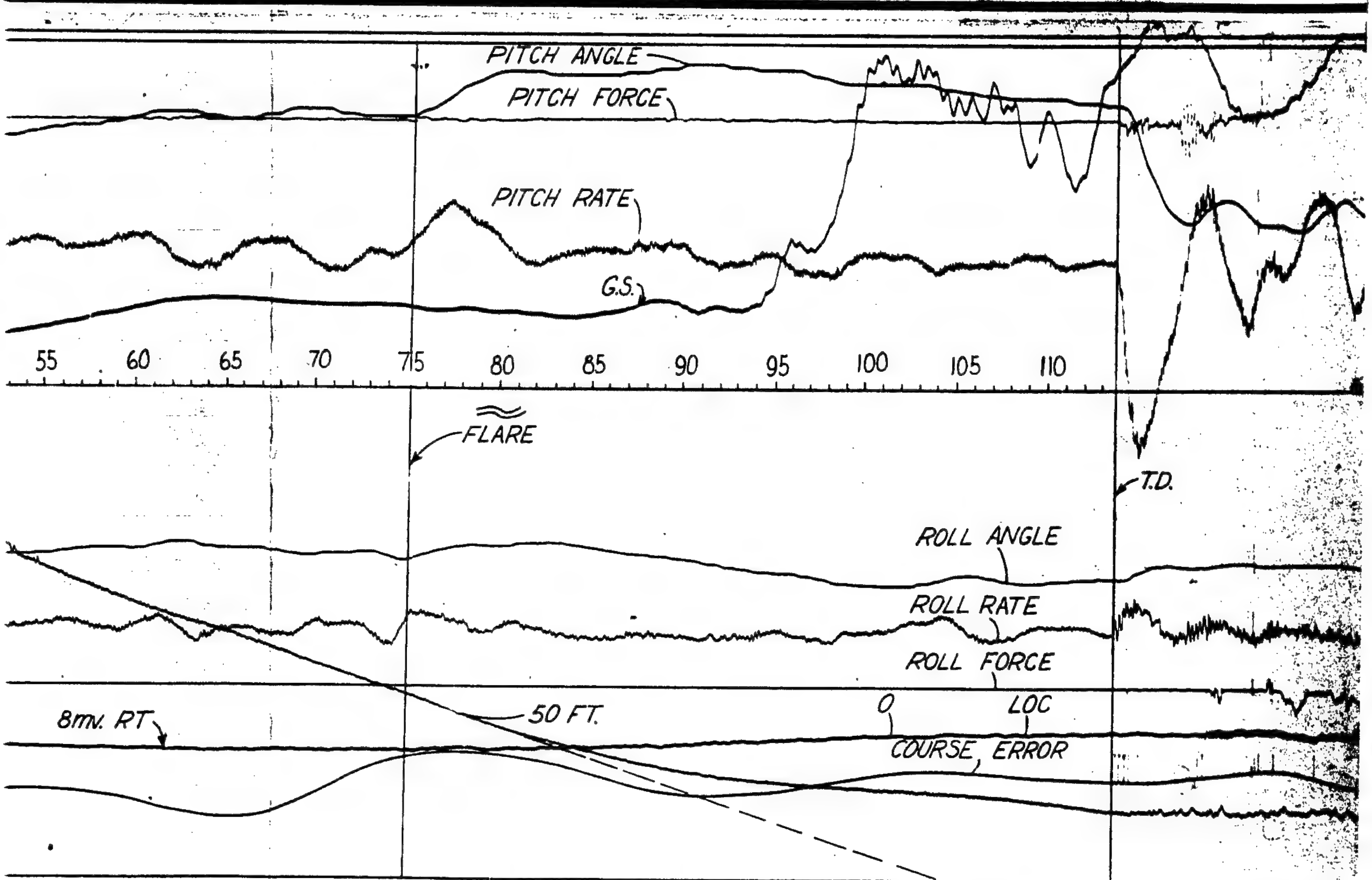
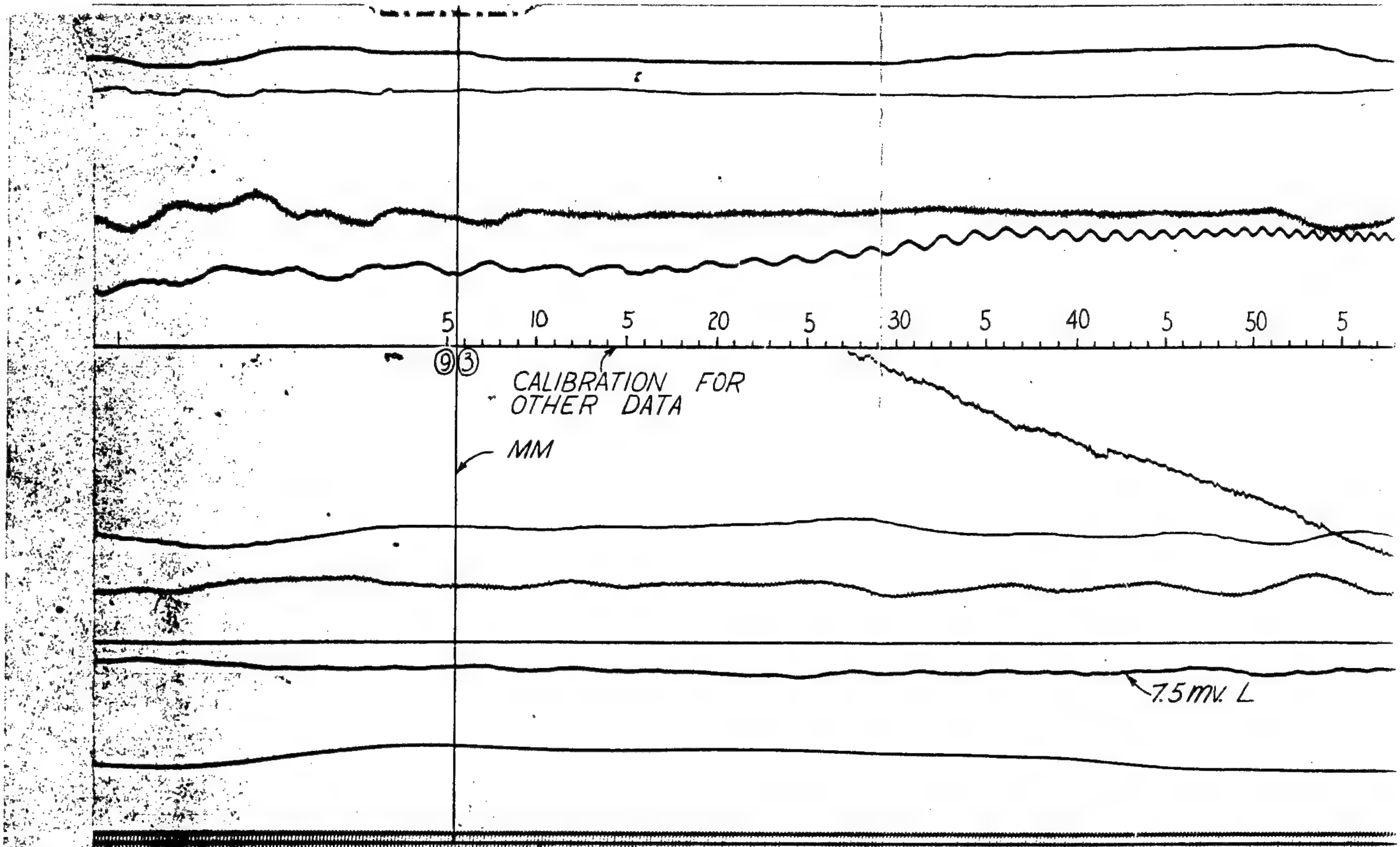
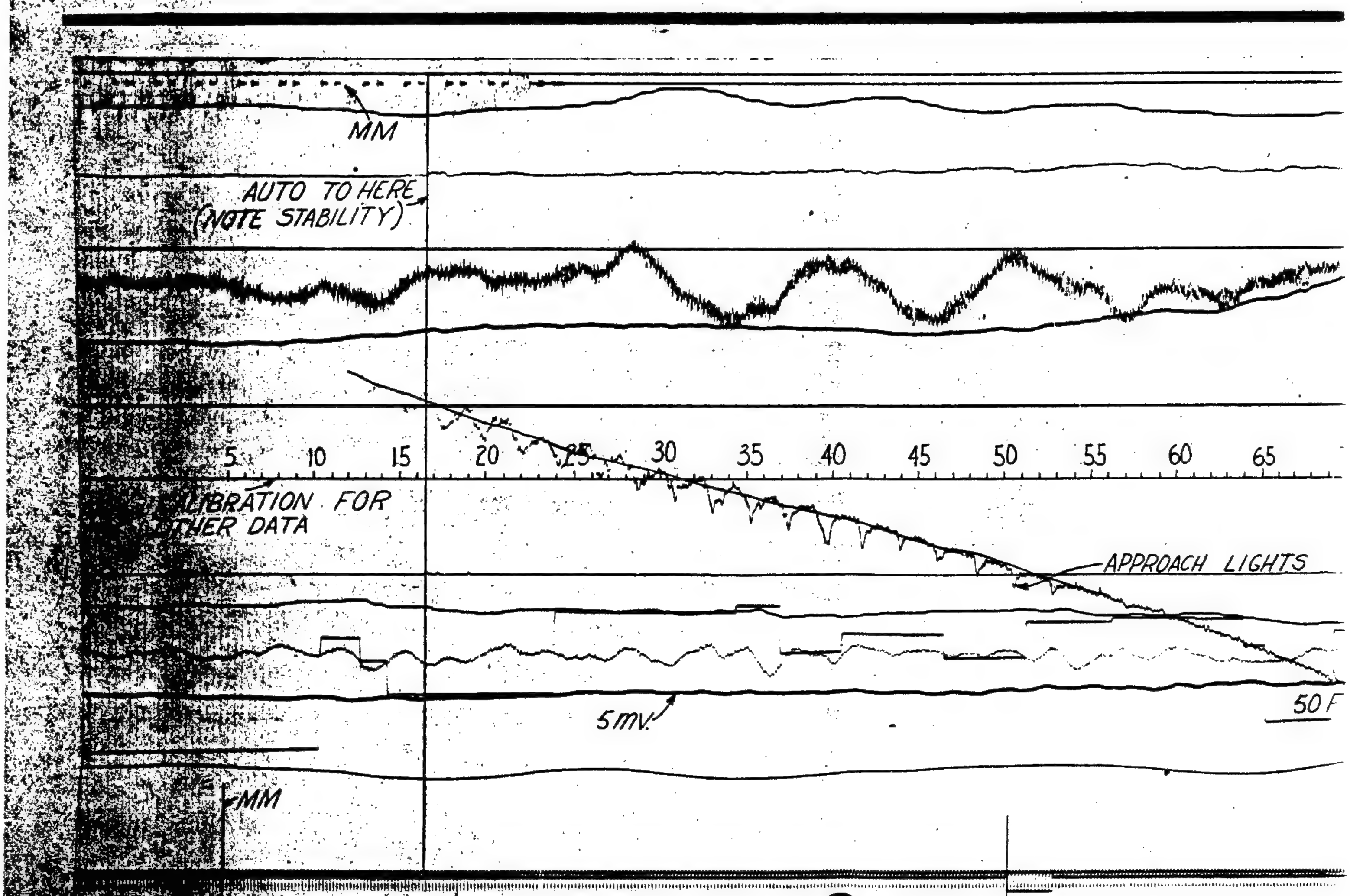


Fig. 59 Oscillograph Recording – Mather AFB, California #2


5
10
5
20
5
30
5
40
5
50
5
9
3
CALIBRATION FOR
OTHER DATA
MM
7.5 mv. L


MM
AUTO TO HERE
(NOTE STABILITY)
5
10
15
20
25
30
35
40
45
50
55
60
65
CALIBRATION FOR
OTHER DATA
APPROACH LIGHTS
50 F
5 mv.
MM

1

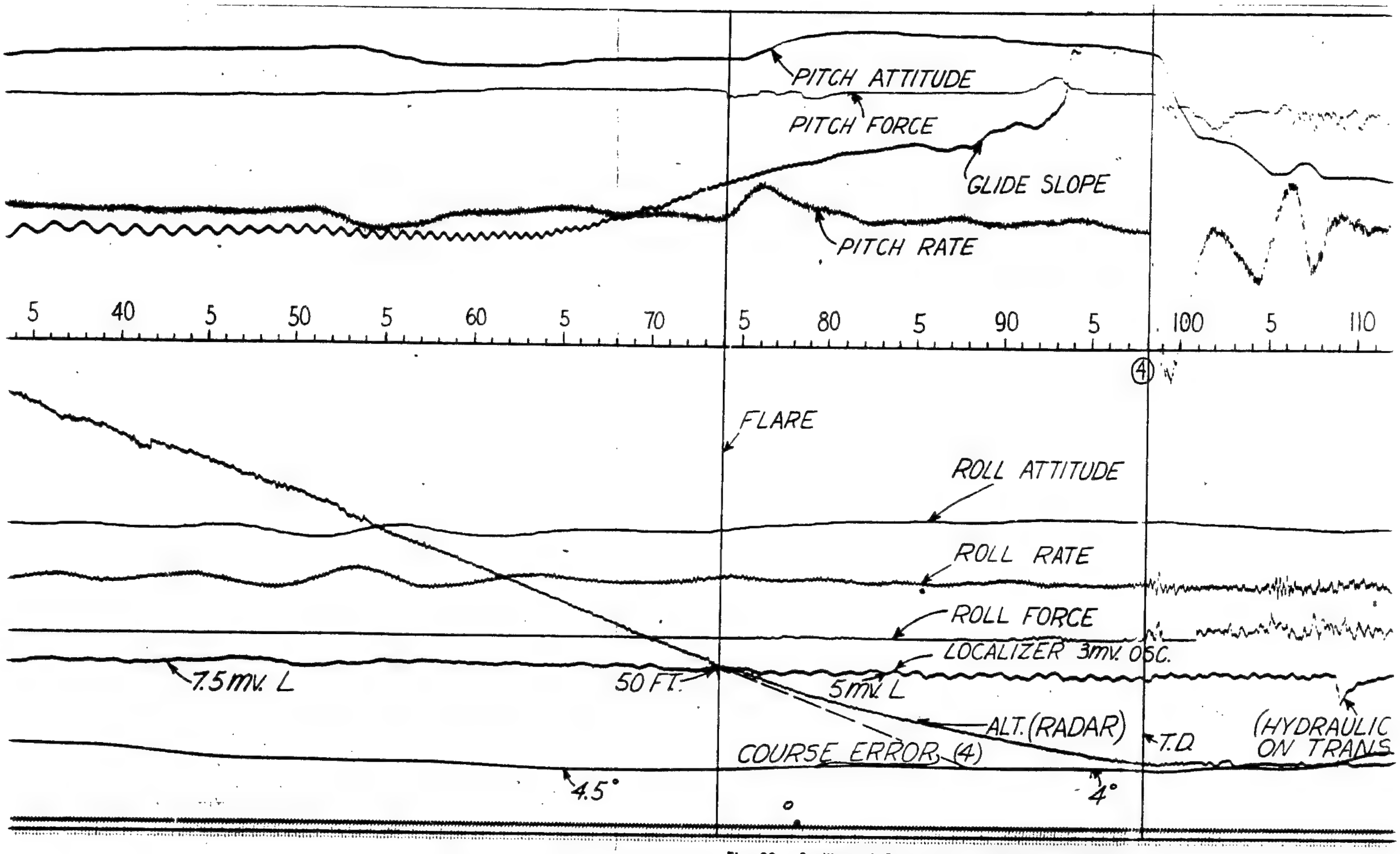
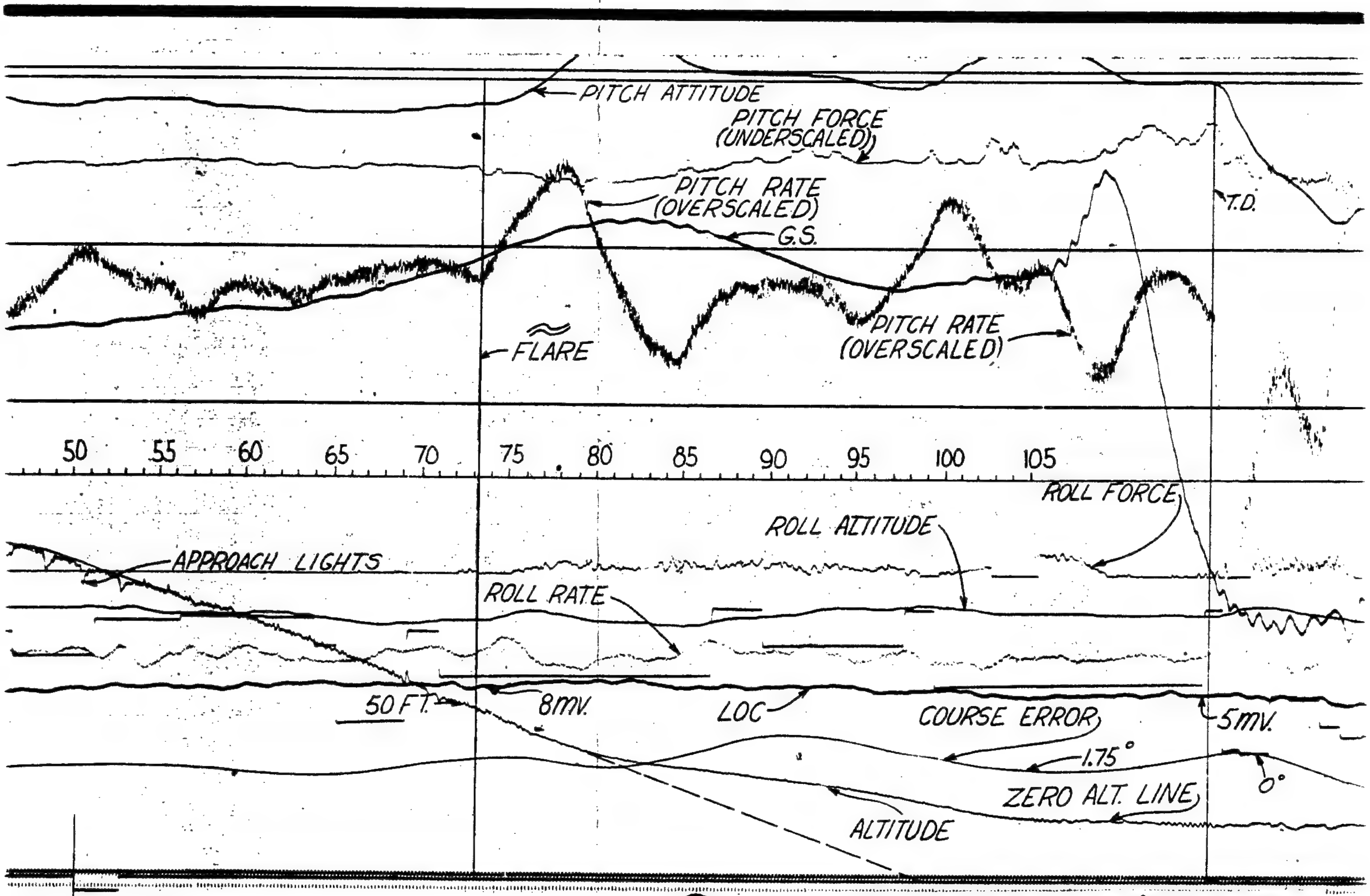


Fig. 60: Oscillograph Recording – Castle AFB, California



②

Fig. 61: Oscillograph Recording – Sacramento Metropolitan, California

10K

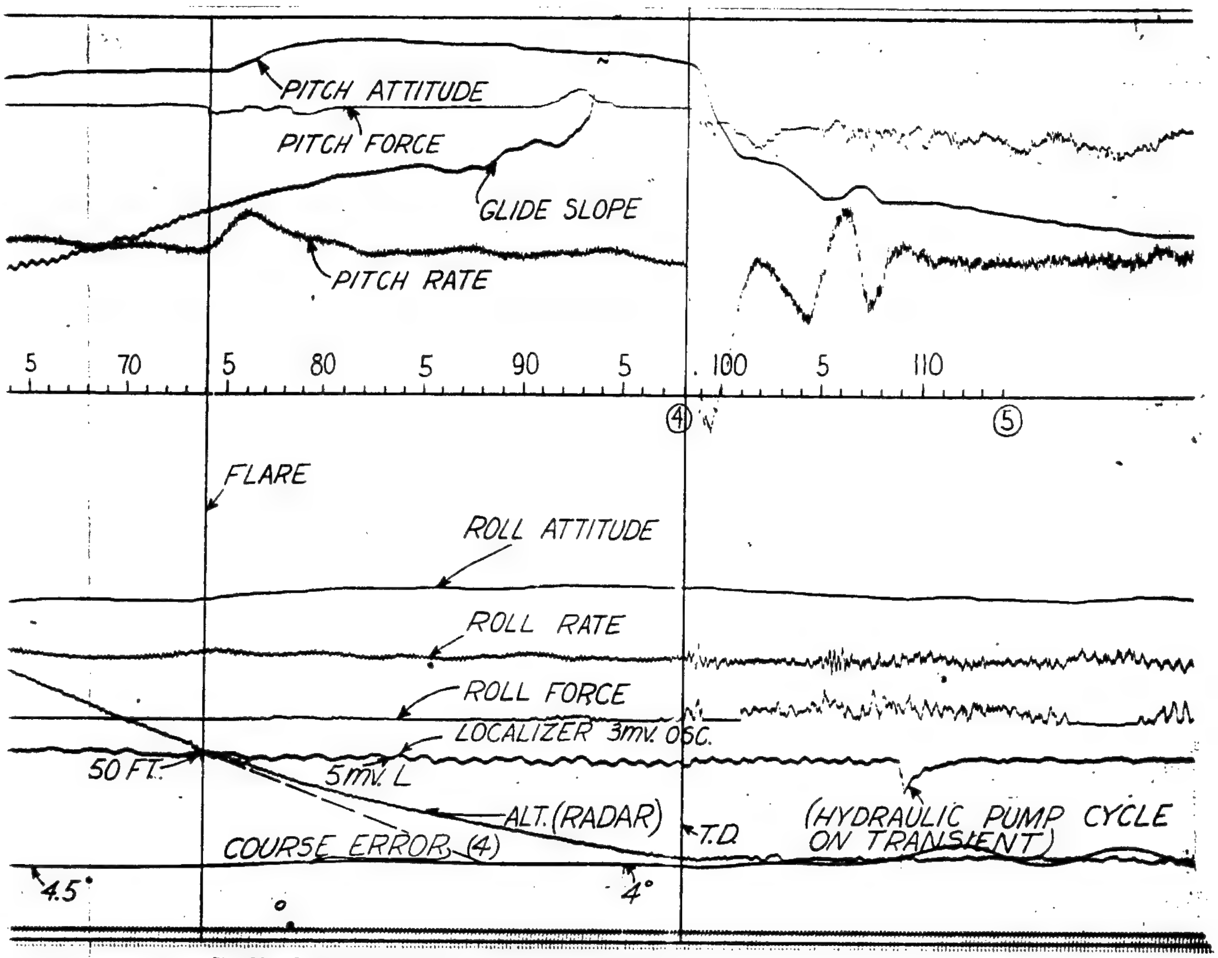


Fig. 60: Oscillograph Recording – Castle AFB, California

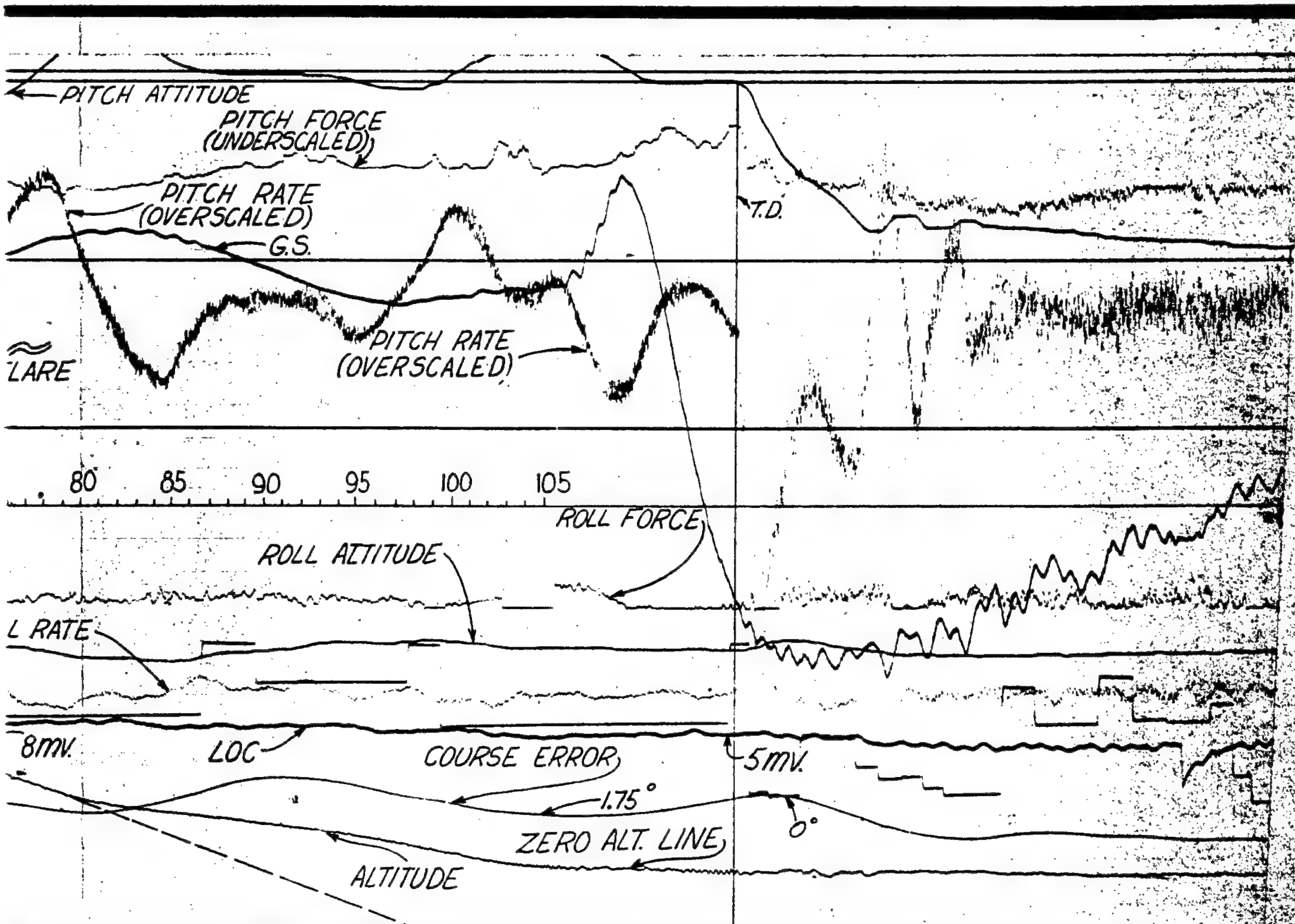
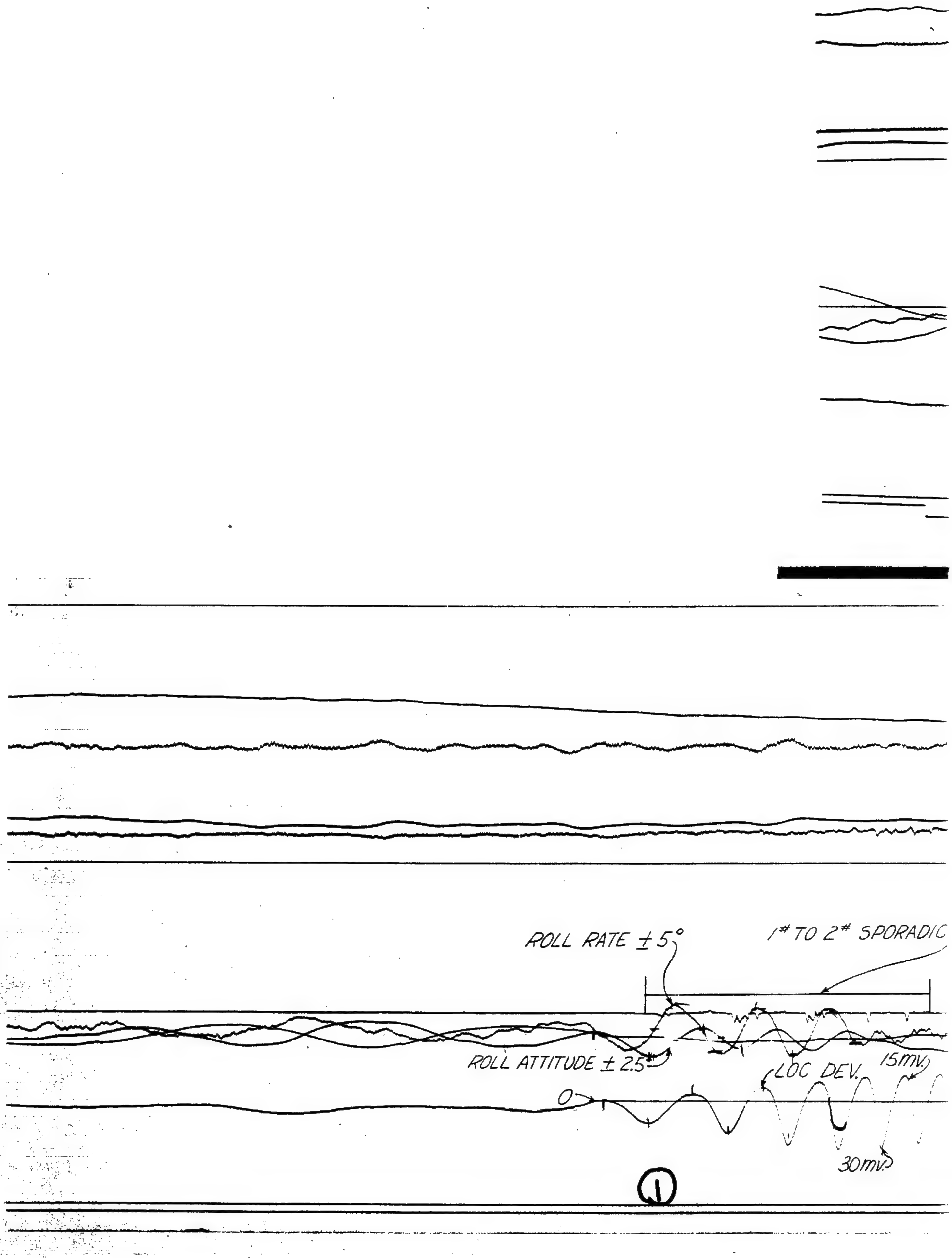


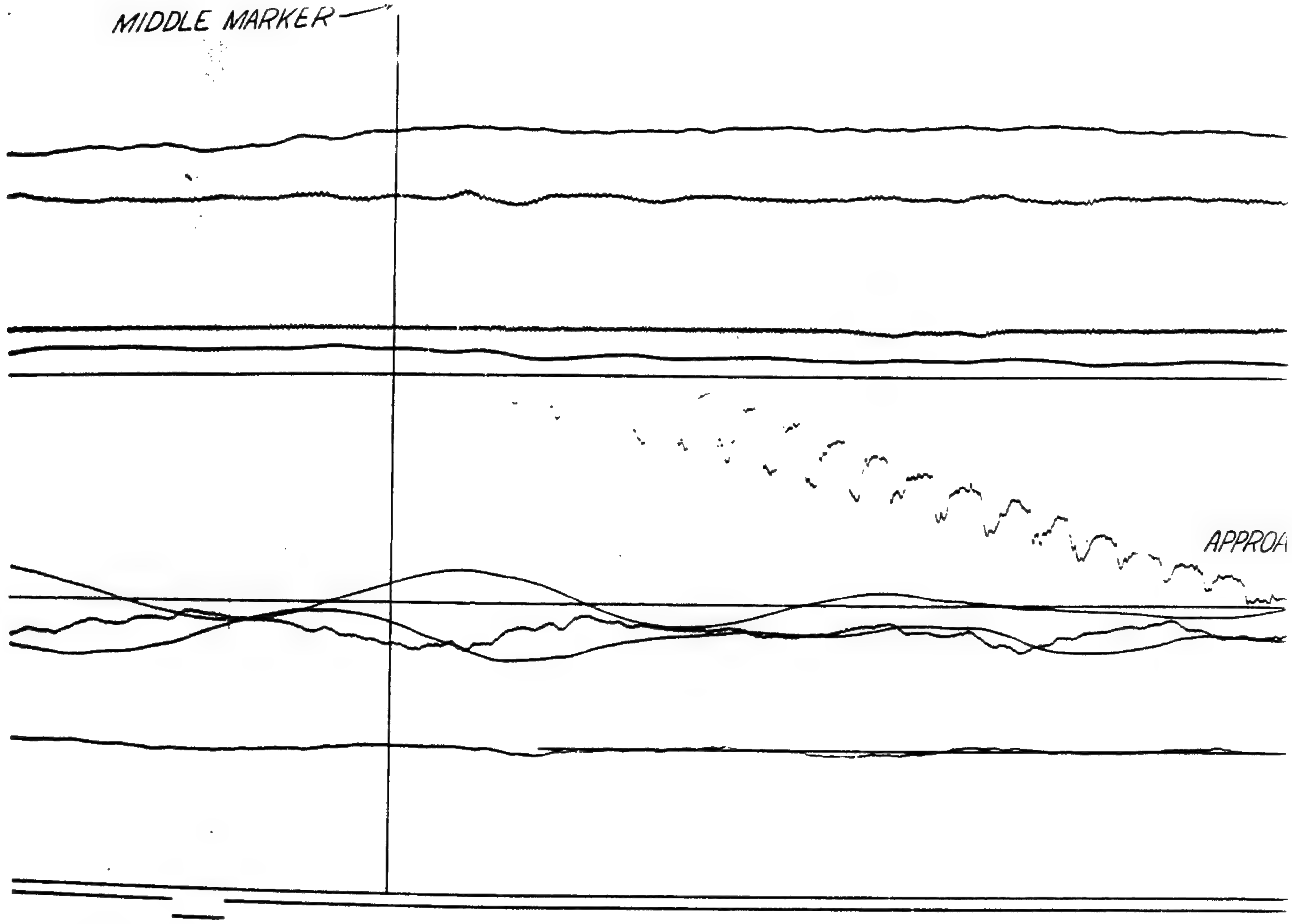
Fig. 61: Oscillograph Recording – Sacramento Metropolitan, California

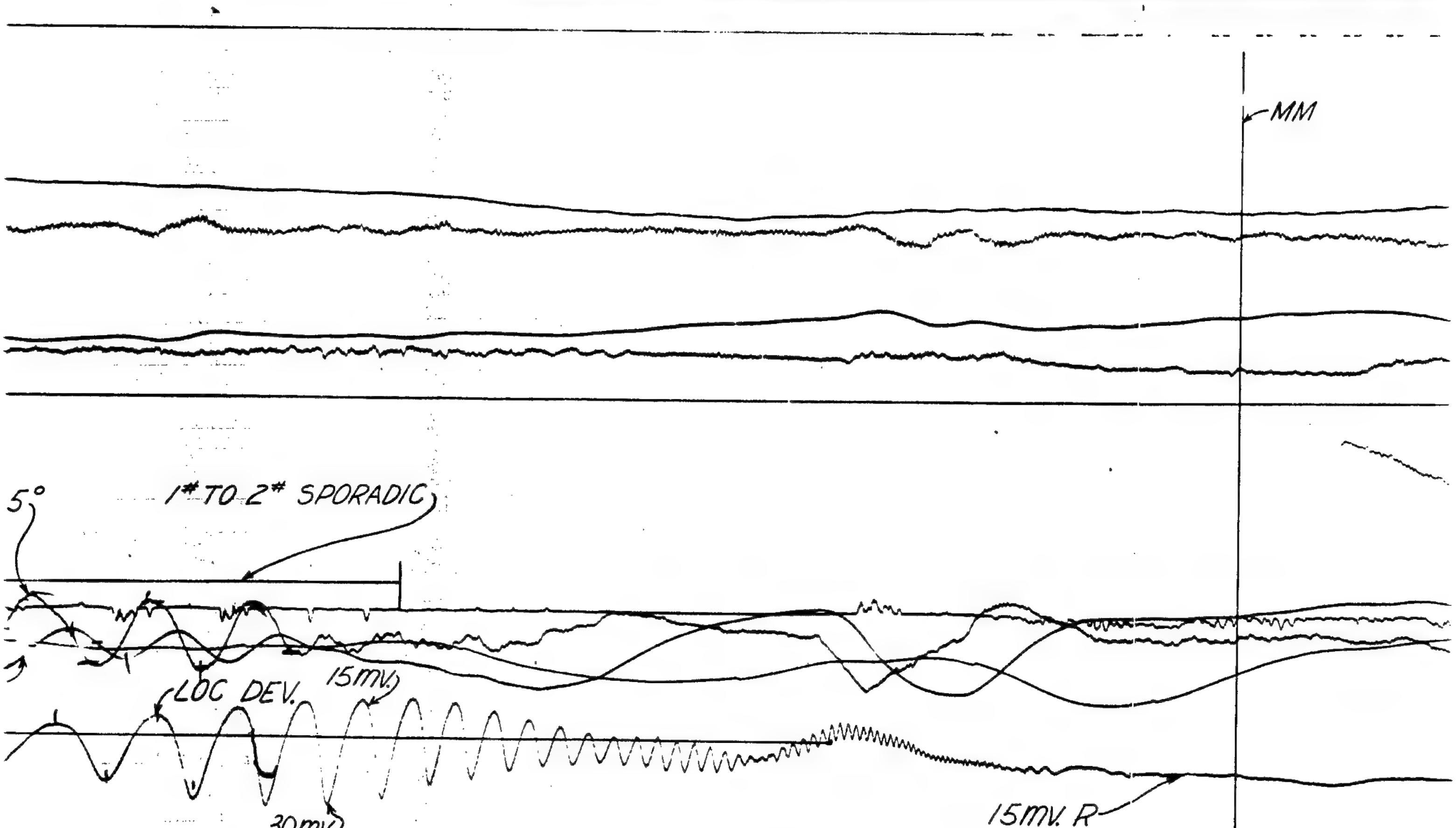
106

3

MIDDLE


ROLL RATE ± 5°
1# TO 2# SPORADIC
ROLL ATTITUDE ± 2.5°
LOC DEV.
15mv.
0
30mv.
1


MIDDLE MARKER
APPROA


MM
5°
1# TO 2# SPORADIC
LOC DEV.
15mv.
30mv.
15mv. R

2

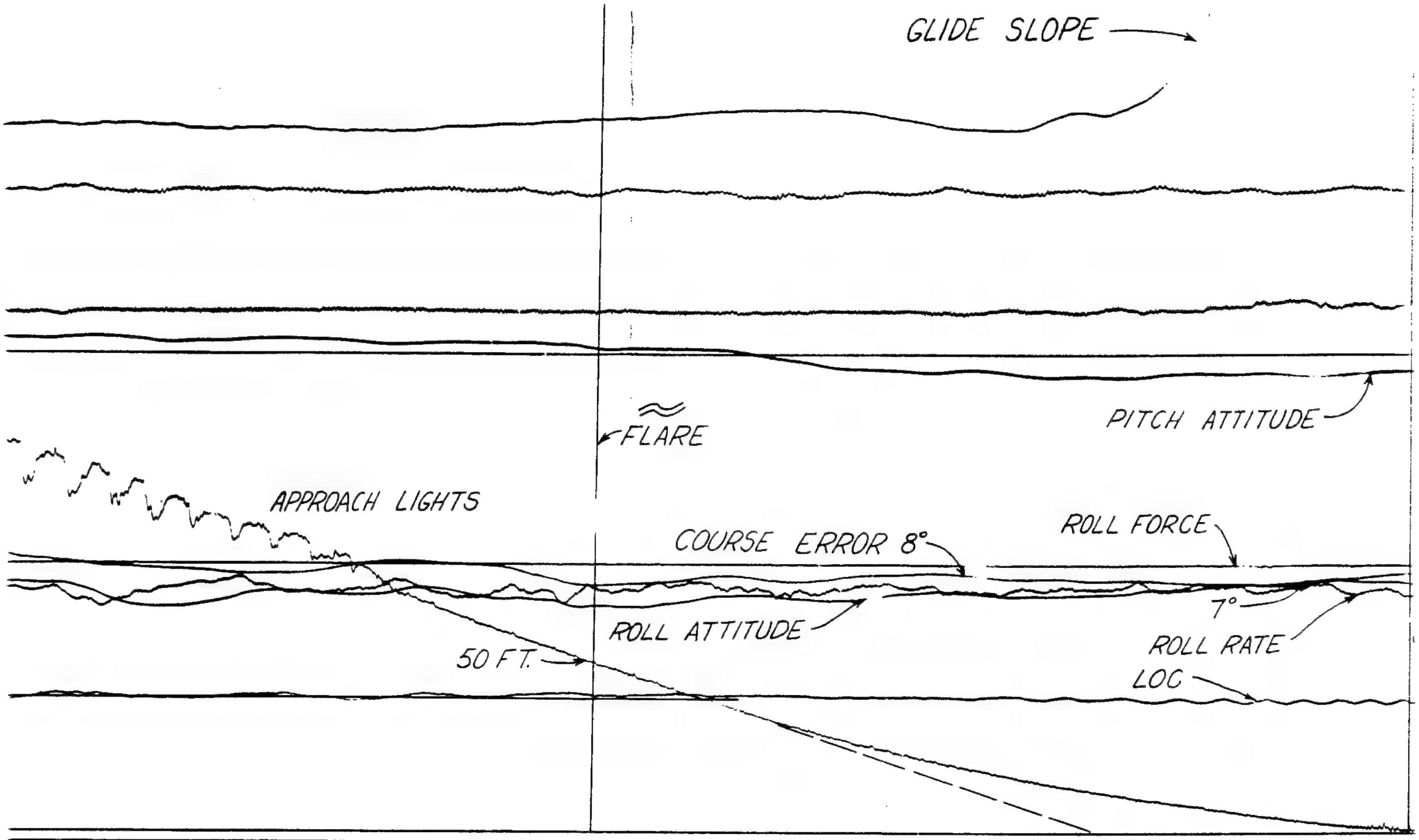


Fig. 62: Oscillograph Recording – Randolph AFB, Texas

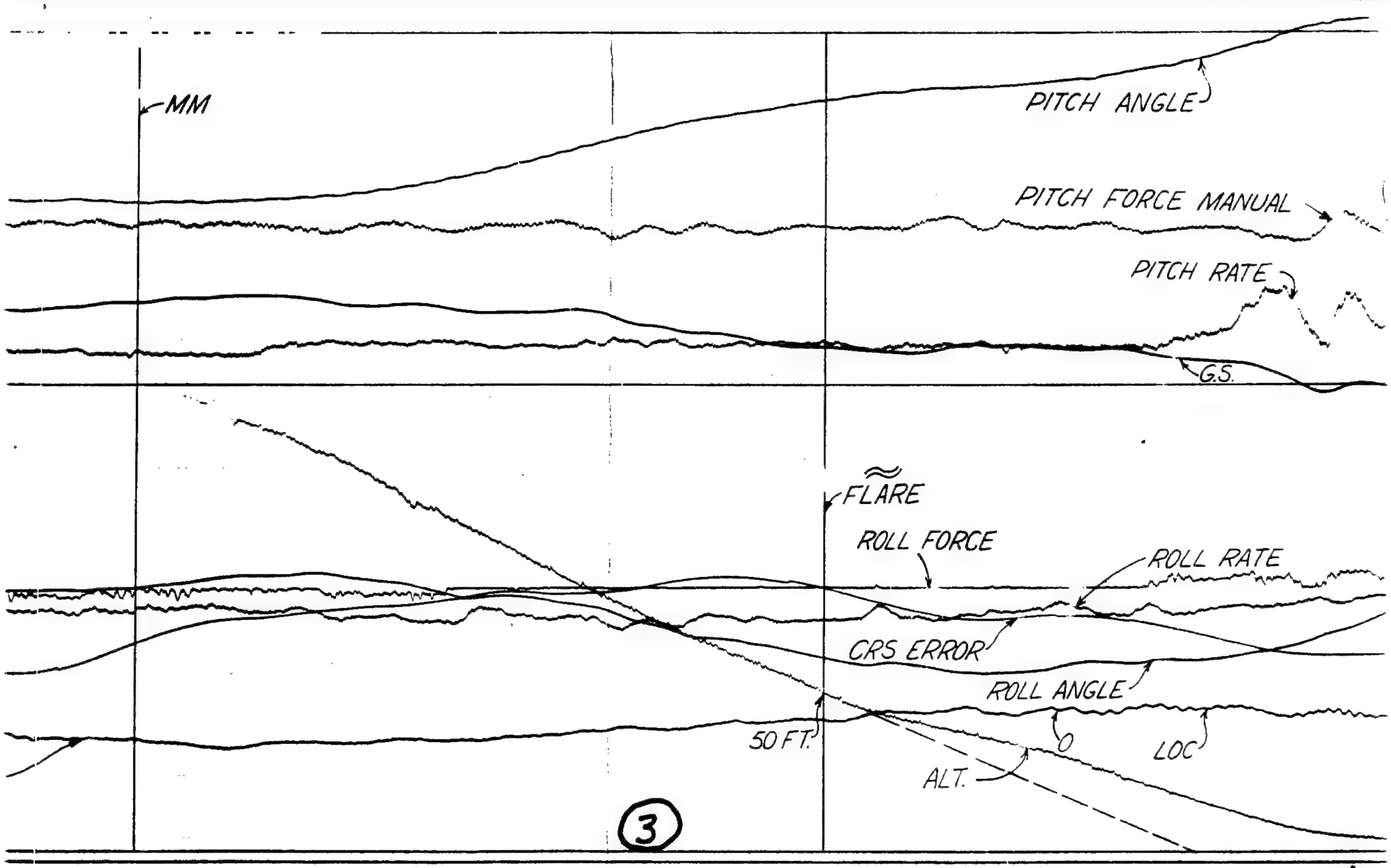


Fig. 63 Oscillograph Recording – Kelly AFB, Texas

1C

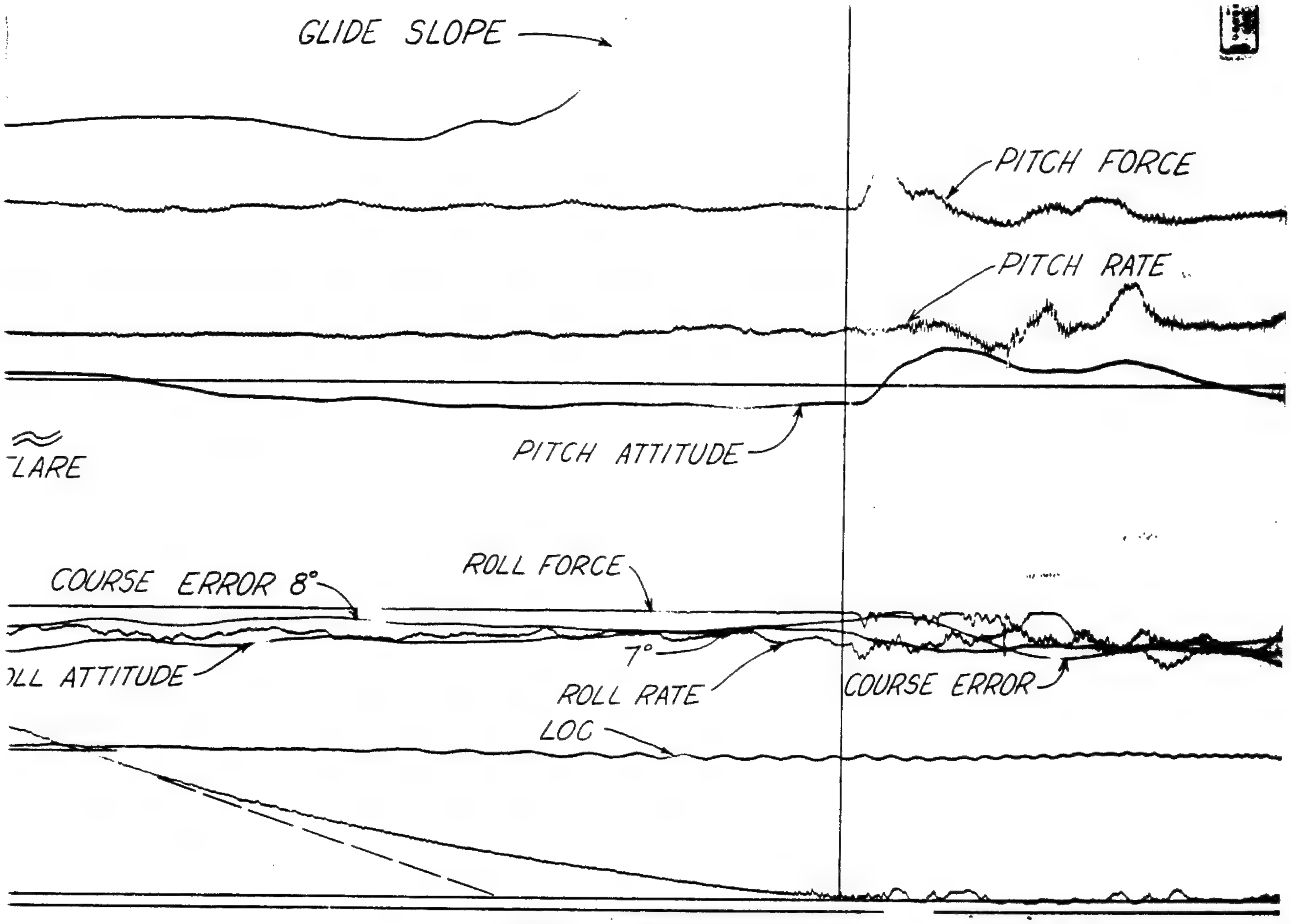


Fig. 62: Oscillograph Recording -- Randolph AFB, Texas

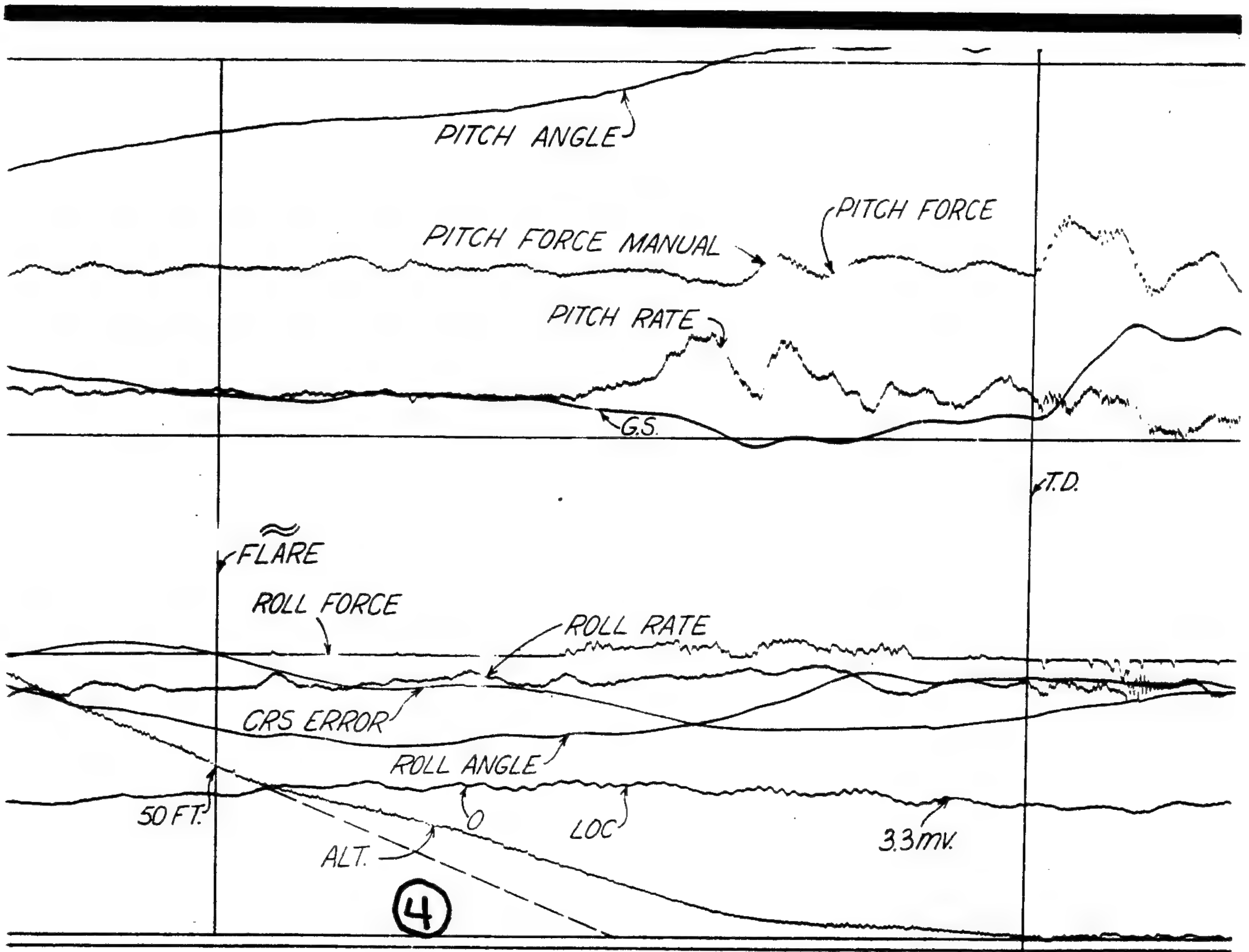


Fig. 63 Oscillograph Recording -- Kelly AFB, Texas

SECTION IV

MECHANIZATION

This section is supplied to provide the reader with a concise yet understandable representation of system mechanization. The thirteen diagrams contained in this section are divided in three groups; namely: Lateral computation (Figures 45 through 49), Longitudinal computation (Figures 50 through 53) and ATS/Speed Command (Figures 54 through 57). The signal flow, computation and numerical notations are representative of the systems as mechanized and flown in the T-39 aircraft test beds. In all cases, representative gains are supplied with a steering bar movement in inches for a given angular or voltage input. In those cases where the AFCS is integrated with the Flight Director System, continuation of the computation is supplied by providing a ratio of steering bar displacement vs. aircraft control surface movement. In all cases where signal shaping is accomplished, the function is graphically portrayed and the numerical value for a single time constant is given.

SECTION V

PERFORMANCE

The performance data presented is representative of system operation under actual flight operation, and in some cases, in minimum weather conditions. It is the intent that the performance data contained present, in simple terms, representative data substantiating, in part, the conceptual approach used in synthesizing the system. All the data is concerned with the approach and touchdown from the middle marker in.

A total of six recorder tapes were selected primarily to illustrate highlights each contained, and still present typical results obtained repetitiously from the numerous approaches flown.

Figure 58 is a recorder tape of an approach and landing at Mather AFB, California. It is typical of a fully automatic landing. Both force signals are relatively quiet until touchdown. Minimum bank angles are required to maintain a near perfect localizer track. The course dispersion is minor (2.5°) and the aircraft is landed with 1.5° crab angle. A course dispersion soon after touchdown is corrected by the pilot. (Note roll force input).

The glide slope dispersion between approximately 150 ft.

absolute altitude and touchdown is typical of the unusability of this parameter during this period. Altitude data is clean and the parameter in this case is usable from approximately 175 ft. to touchdown.

The flare is very pronounced with a definite pitch attitude and pitch rate change; however, the pilot in this case elected to assist the flare (note pitch force input) due to an overshoot in flight path angle which was developing and which would have resulted in a substantially lower vertical velocity and thus an overshoot of the normal touchdown point.

Figure 59 is also a recorder tape of an approach and landing at Mather AFB. Though this was a fully automatic approach, an intentional bi-directional overpower in the roll axis was induced by the pilot at the Middle Marker. Recovery from this input was smooth and positive. The resulting course oscillation resulted in a maximum 8 MA error in the localizer which was eliminated prior to touchdown, since both course error and localizer error were essentially zero at touchdown. Note that following the induced roll overpower, both roll and pitch force signals remain at null indicating a "hands off" landing. The radical glide slope signal dispersion is again very apparent. The flare is very pronounced with a positive pitch attitude excursion and, from the attitude trace, is near optimum with a minor overshoot evident just

prior to touchdown.

Figure 60 is a recorder trace of an approach and landing at Castle AFB, California. This approach indicates a cross wind component requiring approximately 4° of crab angle. (Note the course error). The flare, assisted slightly by the pilot (note minor pitch force inputs), was near optimum. Of primary interest, however, is the difference in the quality of the beam signals.

The glide slope signal typically disperses; however, an oscillation of increasing frequency is evident between the Middle Marker and 50 ft. This oscillation starts at approximately 2 HZ and increases to 8 HZ.

The clean pitch rate and pitch attitude traces indicate a total system rejection of the noise through the whole frequency range, though the beam envelope is being followed realistically by changes in pitch attitude until approximately 100 ft. Here the glide slope signal to the system is faded out and a flight path angle reference becomes the controlling parameter. The localizer signal also displays a low magnitude oscillation of approximately 2 HZ. Total system rejection of this noise is indicated by the lack of roll attitude or roll rate response.

Figure 61 is a recorder trace of an approach and landing at Sacramento Metropolitan Airport. This trace was chosen to illustrate a manual approach. The approach was initiated

fully automatic, but at the Middle Marker the AFCS was intentionally disengaged and the pilot manually flew the aircraft on instruments to touchdown. An overshoot occurred during the flare with a very apparent ballooning effect prior to touchdown. (Note altitude and pitch attitude traces.)

The other significant item in this trace is the effect the approach lights have on the radar altimeter. The phenomenon will appear more drastically on other traces at other locations and precludes utilizing the radar altimeter outputs as a control parameter until well past the lights. A more drastic display is provided in Figure 62 which is typical of approaches made at Randolph AFB, Texas. An additional interest of this trace is the relatively large crab angle (7° course error) required to hold the localizer at null.

Figure 63 is definitely not representative of approach and landings at Kelly AFB, Texas where this recorder trace was taken. This particular approach was being conducted with "split axis", in that the roll axis was automatic and the pitch axis was being flown manually. As is the case in many approaches, it is not unusual for another aircraft to take off while one is on "Final" as long as sufficient separation is assured. Such was the case during this approach and everything was normal to the approaching aircraft until

just outside the Middle Marker. At this time the aircraft taking off was flying over the localizer transmitter site at the opposite end of the runway. The recorder shows the effect on the localizer signal very graphically as a low amplitude, low frequency oscillation builds into a high amplitude, higher frequency oscillation, then into a low amplitude, high frequency oscillation. System response is apparent for the frequency components as indicated by the roll attitude and roll rate traces. As the oscillations increase in frequency, the system rejects them as noise and control activity quickly dampens to the response of the envelope. The roll force inputs of 1 lb. to 2 lbs. are attributed to pilot damping input. The distortion of the localizer occurred over a 15 second period. Within the following 3 seconds and at the Middle Marker full stability has been attained though considerable localizer error resulted. This error was rapidly diminished so that at flare it was neglible. The remaining portion of the profile is typical of a "split axis" approach.

SECTION VI

RECOMMENDATIONS

The recommendations that follow break down into two subject categories. The first subject recommends implementation of promising concepts into the flight test vehicle(s), followed by a planned study accomplished through flight test. The second subject category deals with updating and expanding the capabilities of the basic flight test vehicle(s).

Flight Test Concepts:

1. Resume study of the Lateral Rate Field Display as a trend indicator, coupled with an investigation to establish the usability of the beams provided by various instrument approach and landing systems, from final through rollout.

   Difficulties with the EL displays and the rate field drive circuits prevented a truly qualitative study of the rate field display. However, recent advances in digital circuitry with its inherent flexibility and stability should present a far better opportunity for a flight test program which could result in the desired goals.

2. In association with the lateral rate field display,

determine whether Speed Error rate is feasible as a control and/or display parameter.

Unfortunately the problems with the basic mechanization of the Speed Error rate display, like the Lateral rate display, precluded a qualitative result from what little flight test was accomplished. Again, advances in solid state techniques provide the opportunity for a fruitful flight test of the speed error rate field concept.

3. Continuation of the forward slip as a terminal manuever to eliminate the decrab manuever. Side-Slip is a natural concurrent study with the lateral rate field study. ie: Cross track drift is a major control parameter in the side-slip mode, and the signal requirement is essentially the same as the beam rate parameter established in the rate field study. In addition, the feasibility of employing a rudder command display could be investigated.

4. Evaluate the requirements for absolute control over aircraft direction following touchdown, to insure a safe rollout (on concrete) to a full stop. Also, an evaluation of control requirements resulting from transitions, such as result from heading errors (crab), cross track errors and/or lateral deviations from runway centerline, is suggested.

5. The installation and flight test of an accurate Inertial system. Its implementation could establish a base line for added studies, for example, the investigation of requirements to improve beam tracking through inertial damping.

However, the system's greatest asset would be the preciseness of measurement afforded to any study undertaken. It would essentially provide the ability to measure space vectors (inflight) with the precision of a ground based tracking device. For instance, and essential to earlier recommendations, the INS would prove especially helpful in determining the "quality" of a guidance beam, since the aircraft's actual track is continually being measured.

Flight Test Vehicle:

Of major importance to any flight test program is the test bed employed. In particular, reliability and versatility are essential to maintaining a smooth, on schedule program that will provide constructive data. From this viewpoint it is hoped to establish a recommendation of periodic modernization of the recording Instrumentation System and Control/Display systems employed.

1. For instrumentation, it is recommended that latest

techniques in magnetic tape recording be investigated for incorporation. Completely versatile, these systems can provide a ten-fold increase in the number of channels recorded, reduce the data automatically in a fraction of the time and have practically unlimited selection as to what type of date is desired for reduction.

2. One of the primary objectives to most of the flight test programs has been the investigation and evaluation of flight control and display concepts. It becomes apparent that the test system employed must provide the accuracy and reliability required to meet the test objectives.

Of necessity, and to meet the changing requirements of new concepts to be studied, the Control/Display System is continually undergoing change, either through modification of existing equipment or interfacing of new equipment. Thus, time becomes an enemy, not only from age with its own problems of equipment reliability, but also from the saturation of equipment modification and limitations in outdated electronics in both function and interface compatibility.

It is recommended that consideration be given to updating at least one aircraft with a system embodying the concepts and capabilities presented in this report, as a minimum

requirement. In addition, it is suggested that plans and programs be reviewed as far forward as possible and known system requirements incorporated with those already presented in the report.

It is intended that the above planning would postpone the saturation of modification capacility by a substantial period.

SECTION VII

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